



# **Development of Systems Engineering Maturity Models and Management Tools**

## **Final Technical Report 2011-TR-014**

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## 14. ABSTRACT

As current United States Department of Defense (DoD) system development and engineering activities continue to be challenged by formulation of larger and more complex systems, DoD's methods, processes, and tools (MPT) for effectively and efficiently addressing these challenges are likewise being challenged. The goal of this research was to develop a mixed methodological approach to examine systems development maturity. Qualitatively we intended to uncover and investigate the key characteristics that drive the development of large scale, complex systems. Quantitatively we used these key characteristics to formulate a collection of analytical MPT to assist in making informed systems engineering management decisions. To advance the state of practice of this research, all MPT developed under this task were validated through application on designated projects. The validation effort was designed to determine if they could be effectively implemented as a best practice across the Department of Defense. The need for this research is precipitated by the need for system engineering, development, and cost models that adequately incorporate the unique aspects of system and technology insertion and integration. This was then predicated on the following task objectives &#61623; Leverage prior investments made in the System Readiness Level (SRL) body of knowledge to explore the effects of technology and integration maturity on systems engineering effort and cost &#61623; Expand the scope and applicability of the SRL to address potential systems engineering MPT; and &#61623; Enhance current SRL methods and tools to incorporate research-derived insights, provide expanded functionality, and demonstrate the utility of the tools in the context of a pilot project. At present, the SRL is a descriptive model that characterizes the effects of technology and integration maturity on a system engineering effort, particularly with respect to integrating discrete functional systems into a coherent mission capability. The SRL model, as developed by the Systems Development & Maturity Laboratory (SysDML) at Stevens Institute of Technology, has been validated by the NAVSEA PMS 420, Littoral Combat Ship Mission Module Program Office in collaboration with Northrop Grumman Corporation which used it to monitor development and integration progress from a system perspective. The SRL and supporting assessment methodology has proven itself to be a promising mechanism for understanding the effects of technology and integration maturity in a systems engineering context. This task extends the research to better characterize the drivers of integration effort, and to explore application of the SRL to broader areas of the systems engineering management, where validated models and supporting tools are lacking.

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## ABSTRACT

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- Leverage prior investments made in the System Readiness Level (SRL) body of knowledge to explore the effects of technology and integration maturity on systems engineering effort and cost;
- Expand the scope and applicability of the SRL to address potential systems engineering MPT; and
- Enhance current SRL methods and tools to incorporate research-derived insights, provide expanded functionality, and demonstrate the utility of the tools in the context of a pilot project.

At present, the SRL is a descriptive model that characterizes the effects of technology and integration maturity on a system engineering effort, particularly with respect to integrating discrete functional systems into a coherent mission capability. The SRL model, as developed by the Systems Development & Maturity Laboratory (SysDML) at Stevens Institute of Technology, has been validated by the NAVSEA PMS 420, Littoral Combat Ship Mission Module Program Office in collaboration with Northrop Grumman Corporation which used it to monitor development and integration progress from a system perspective. The SRL and supporting assessment methodology has proven itself to be a promising mechanism for understanding the effects of technology and integration maturity in a systems engineering context. This task extends the research to better characterize the drivers of integration effort, and to explore application of the SRL to broader areas of the systems engineering management, where validated models and supporting tools are lacking.

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# 1 SUMMARY

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At present, the System Readiness Level (SRL) developed by the Systems Development & Maturity Laboratory (SysDML) at Stevens Institute of Technology is a descriptive model that characterizes the effects of technology and integration maturity on a systems engineering effort, particularly with respect to integrating discrete functional systems into a coherent mission capability. This research expanded upon this work to develop a mixed methodological approach to examine systems development maturity.

Qualitatively we continue to uncover and investigate the key characteristics that drive the development of large scale, complex systems. Quantitatively we used these key characteristics to formulate a collection of analytical methods, processes, and tools (MPT) to assist in making informed systems engineering management decisions.

To advance the state of practice of this research, the MPT developed under this task were validated in a collaborative research effort with the US Navy NAVSEA PMS 420, Littoral Combat Ship Mission Module Program Office and Northrop Grumman Corporation on the US Navy NAVSEA PMS 420, Littoral Combat Ship Mission Module Program. Through this validation, the SRL and supporting assessment methodology as developed in this research have proven to be a promising mechanism for understanding the effects of technology and integration maturity in a systems engineering context. In addition, the MPT research and development under this task have demonstrated utility for defining system status and providing leading indicators of development risks. **The success of the SRL's implementation thus far highlights the potential benefits of** extending the research to better characterize the drivers of integration effort, and to explore application of the SRL to broader areas of the systems engineering domains, particularly with respect to large scale, complex implementations, where validated models and supporting tools are lacking.

In summary, the work performed in this task by the SysDML of Stevens Institute of Technology in conjunction with Texas A&M University was partitioned into four areas linking SRL to development architectures, milestones, and costs:

1. Aligning SRL Methods with Architectures
2. Mapping SRL/ITRL to Development Activities/Status
3. Leveraging SRL Relationships to Allocate Resources
4. TRL and IRL Evaluation Linkage to Performance Measures

## 2 INTRODUCTION

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Current United States (US) Department of Defense (DoD) system development and engineering activities continue to be challenged by formulation of larger and more complex systems or systems of systems (SoS). In many ways, these development paradigms are contesting many of the engineering, management, and acquisition practices that have been used for decades in the development of stand-alone systems. Similarly, complex system development has made the management of systems engineering activities more difficult to monitor and control due to the exponential growth of technologies and integrations being incorporated under a common effort. Thus, there is a growing need for more systematic and systemic approaches to monitoring development and integration of systems. This necessitates the development of new methods, processes, and tools (MPT) through best practices in order to govern the many unique aspects of systems development and acquisition programs, and be able to compare actual progress against planned accomplishment from a technical perspective. In a continued effort to address some of these issues, this report summarizes the research performed under this task by the Systems Development & Maturity Laboratory (SysDML) at Stevens Institute of Technology in system maturity assessment for developmental lifecycles.

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### 2.1 RATIONALE FOR DEVELOPMENT OF SYSTEM MATURITY ASSESSMENT

In 1999, the US General Accounting Office (GAO) (now the Government Accountability Office) stated that there were few metrics used within the DoD to gauge the impact of investments or the effectiveness of processes used to develop and transition technologies, and additional metrics in technology transition were needed (GAO, 1999). In 2002, the GAO further articulated that the DoD needed to enable success through the demonstration of value and the credibility of new processes using metrics (GAO, 2002). To address these compounding challenges, in 1999, the DoD began implementing the Technology Readiness Level (TRL) as a metric to assess the maturity of a **program's** technologies before its system development began. Additionally, the DoD made constructive changes to its approaches to acquisition that would address these issues by **ensuring a weapon systems' technologies are demonstrated to a high level of maturity** before beginning its program and using an evolutionary or phased approach to developing such systems (GAO, 2006). More recently, the successful implementation of TRL within the DoD has been noted by the GAO (Sullivan, 2010).

Even with the implementation of new processes and practices within DoD acquisition and systems engineering, the challenges are still significant. Nowhere is the need for enhanced monitoring capabilities more visible for systems than in the development of

complex systems. Thus far, the TRL scale has been a key gauge of the current status of maturity of a given technology and even systems within DoD by monitoring capability development from concept definition through operations and support. In countless development efforts TRL has been a key indicator of progress and aided dramatically in keeping programs on track and adjudicating the perceived maturity of a technology for acquisition into a program. It has additionally been incorporated as a decision criterion in the Defense Acquisition Milestone process (see DoD 5000.02) along with other government agency guidance, i.e. National Aeronautics and Space Administration Systems Engineering Handbook (NASA/SP-2007-6105).

Consequently, despite the utility and value of the TRL as a metric for determining technology maturity before transitioning into a system, TRL was not intended to address system integration or to indicate that the technology will result in successful development of a system. Additionally, when TRL is applied to components within a complex system, the model of using individual technology maturity as a measure of readiness to integrate into system development can become confounded. Similar problems also become apparent with many other technology development tools when applied in a systems context. These challenges and limitation of TRL were expressed by the Honorable Ashton Carter, the Under Secretary of Defense for Acquisition, Technology, and Logistics (AT&L), in his Memorandum for Acquisition Professionals entitled, **“Better Buying Power: Guidance for Obtaining Greater Efficiency and Productivity in Defense Spending.”** He states,

*Reform TRL reviews to focus on technology as opposed to engineering and integration risk. The TRL review and certification process has gown well beyond the original intent and should be reoriented to an assessment of technology maturity and risk as opposed to engineering or integration risk. I am directing the DDR&E to review this process and to make recommendations to refocus the TRL certification process to be consistent with its original intent.*

While the TRL has been well proven for its effectiveness in gauging individual technology maturity in research and development applications, its extrapolation to more complex systems integration (e.g., SoS), dictated by emerging DoD requirements, brings about a host of issues. By looking only at the status of individual component technical maturity, TRL fails to account for the complexities involved in the integration of these components into a functional system and creates the opportunity for performance gaps to remain hidden until late in the development cycle. In other words, application of TRL to systems of technologies is not sufficient to give a holistic picture of system readiness since TRL is only a measure of an individual technology. Furthermore, assessments taking into account several technologies rapidly become very complex without a systematic method of comparison of the technologies and their status as they relate to one another. Finally, multiple TRLs do not provide insight into integration between technologies or the maturity of the resulting system. This monitoring of integration

status is critical as it has been repeatedly shown that most complex system development efforts fail at the integration points. This lack of insight and the need to provide a method for monitoring of integration status led to the development of complementary concepts (e.g. Integration Readiness Level, Manufacturing Readiness Level) that expounds on the traditional TRL with the development of other criteria to gain a more complete perspective of system maturity.

Previous research conducted by the SysDML has begun the development of a Systems Maturity Assessment (SMA) methodology that pairs the traditional TRL scale with an additional series of criteria known as the Integration Readiness Level (IRL) to gain a more complete perspective of system maturity. The foundation of the SMA methodology considers each technology, but instead of being a stand-alone metric for determining readiness, it is analyzed in concert with both its integration requirements and the maturity of other technologies with which it interfaces. In addition, this approach is intended to gain insight into potential risks related to developmental maturity, but not to be a tool for making engineering design risk decisions.

A process has been developed that uses the SMA methodology with a measurement (i.e. System Readiness Level) to assess the maturity of a system under development and make program decisions to capitalize on this information. The SMA methods have been implemented most notably by the US Navy PMS 420, Littoral Combat Ship Mission Module Program Office. SMA has been highly successful on the program and has paid dividends in terms of both increasing decision maker visibility into true system status and allowing for pre-emptive actions to be taken to mitigate potential developmental issues. The program office is now looking at building upon the current SMA methodology and expanding it to new uses in guiding technology selection, insertion and tradeoffs, as well as for use in cost modeling to understand the impacts of implementing technology options. This research and report describe some of these efforts.

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## 2.2 EXISTING ACQUISITION ENVIRONMENT AND GUIDANCE

In program management for acquisition, resources are frequently allocated with the purpose of executing tasks to maintain schedule and budget. This can distract from the ultimate objective of developing a product (or system) to satisfy a customer. A fundamental challenge to solving this problem is that when attempting to meet the emergent needs of the warfighter, program managers will often continue the development of a system through the acquisition lifecycle—even while they coordinate the design activities with preliminary, ambiguous, or subjective information. The balance between customer needs (e.g., warfighter) and design activities for acquisition can create a delicate balance between the overview required by the program manager to make strategic acquisition decisions and the detail that is the focus of the system developers and engineers.

In 2009, the One Hundred Eleventh Congress of the US enacted legislation that was focused on the improvement of the organization and procedures of the DoD for the acquisition of major weapon systems. This act specifies the establishment of positions and activities within the DoD for assessment of technology maturity, consideration of trade-offs among cost, schedule, and performance objectives, and identification and mitigation of systemic problems in major defense acquisition programs prior to Milestone B approval. In an ongoing effort for acquisition reform, the DoD has also released the Technology Readiness Assessment (TRA) Deskbook and issued and updated DoD Instruction 5000.02 and DoD Directive 5000.01.

For example, DoD Instruction 5000.02 describes the System Capability and Manufacturing Process Demonstration, which is intended to demonstrate the ability of the system to operate in a useful way consistent with the approved key performance parameters (KPPs) and that system production can be supported by demonstrated manufacturing processes. Developmental test and evaluation, early operational assessments, and, where proven capabilities exist, the use of modeling and simulation to demonstrate system/system-of-systems integration is critical during this effort. In addition, 5000.02 requests the program manager to prepare an Acquisition Strategy to guide activity during Engineering and Manufacturing Development (EMD). Among other requirements, the Acquisition Strategy must describe the relationship and associated dependencies with other system elements if a program is part of a system-of-systems or family-of-systems.

Additional DoD References and Guidance on Acquisition:

- DoD Directive 5000.01 The Defense Acquisition System – Provides management principles and mandatory policies and procedures for managing all acquisition programs
- DoD Instruction 5000.02 Operation of the Defense Acquisition System – Establishes a simplified and flexible management framework for translating capability needs and technology opportunities, based on approved capability needs, into stable, affordable, and well-managed acquisition programs that include weapon systems, services, and automated information systems.
- Defense Acquisition Guidebook Chapter 4.3.2.4.2.4 Technology Readiness Assessment – A systematic, metrics-based process that assesses the maturity of critical technology elements (CTEs), including sustainment drivers.
- Introduction to Defense Acquisition Management, Defense Acquisition University
- Technology Readiness Assessment Deskbook DUSD(S&T) – Description of suggested best practices, roles, and procedures for meeting the Technology Readiness Assessment requirements of the Defense Acquisition System.



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## 2.3 MATURITY MONITORING PRACTICES

There have been many attempts to identify alternative readiness/maturity levels that will complement TRL, such as Design Readiness Level, Manufacturing Readiness Level, Software Readiness Level, and Operational Readiness Level. While the DoD has relied on some of these subjective assessment techniques for developing the program overview, which then becomes the basis for making strategic acquisition decisions, these subjective assessments are labor-intensive, error-prone, and inadequate for the desired management controls. Notwithstanding the limitations of many of these metrics, any metric should not lose sight of what makes it effective and efficient in an organization (Dowling and Pardoe, 2005):

1. The way the value is used should be clear.
2. The data to be collected for the metric should be easily understood and easy to collect.
3. The method of deriving the value from the data should be clear and as simple as possible.
4. Those for whom the use of the metric implies additional cost should see as much direct benefit as possible (i.e., collecting the data should not cost more than its value to the decision process).

Fundamentally, these controls should be based on system and acquisition attributes that can be quantitatively measured using system metrics. The tension between subjectivity and detail is rationalized through prescriptive techniques, which allow people to make better decisions by using normative models, but with knowledge of the limitations and descriptive realities of human judgment. Thus, further detail is needed into the assessment and use of some of these metrics in order to limit the subjectivity and increase the rigor in their use. It is also important to note that a variety of tools and approaches should be applied to gauge overall development status. The TRA Deskbook notes that, **“the TRA should not be the sole means of discovering technology risk,”** meaning other scales must be applied in order to adequately capture system risk. Therefore, while this research and supporting report address some of these challenges for assessing maturity of system development, there is still significant work to be done to increase the reliability, efficiency, and effectiveness of system maturity assessment.

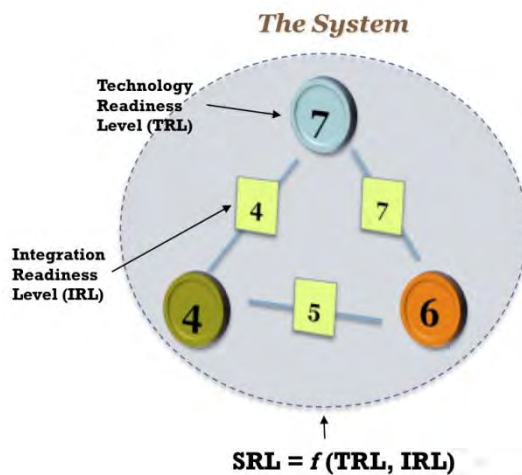
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## 3 SRL FOUNDATIONS

Given the emerging requirements for a measure of complex system readiness, in 2006 the SysDML at Stevens Institute of Technology presented the concept of a System Readiness Level for managing system development (Sausser et al., 2006). As a result, in 2007 the SysDML in collaboration with the US Navy PMS 420/SPAWAR and Northrop



Grumman Corporation were chartered to define a system maturity scale and supporting methodology. The core requirements included that the scale must be robust, repeatable, and agile so outputs could not only be trusted and replicated, but that the methodology as a whole be easily transferred to a variety of different applications and architectures. In response to this challenge, the concept of a System Readiness Level (SRL) that would incorporate a TRL and an Integration Readiness Level (IRL) was developed as depicted in Figure 1 (Sauser et al., 2006)



**Figure 1: System Readiness Level**

Similar to TRL, the IRL was defined as a series of levels that articulate the key maturation milestones for integration activities. The introduction of an IRL to the assessment process not only provided a check as to where a technology was on an integration readiness scale but also presented a direction for improving integration with other technologies. Just as a TRL is used to assess the risk associated with developing technologies, the IRL is designed to assess the risk associated with integrating these technologies. Building upon similar efforts to define an integration maturity scale, the IRL has been refined to include nine levels as represented in Table 1. For more details on the formulation of the IRL see (Sauser et al., 2010). Appendix A contains a further breakdown of the activities associated with each IRL level, and a Subject Matter Assessment of the criticality of these activities as they relate to their respective level.

**Table 1: Integration Readiness Level**

	IRL	Definition	Description
<b>PRAGMATIC</b>	<b>9</b>	Integration is <b>Mission Proven</b> through successful mission operations.	IRL 9 represents the integrated technologies being used in the system environment successfully. In order for a technology to move to TRL 9 it must first be integrated into the system, and then proven in the relevant environment, so attempting to move to IRL 9 also implies maturing the component technology to TRL 9.
	<b>8</b>	Actual integration completed and <b>Mission Qualified</b> through test and demonstration, in the system environment.	IRL 8 represents not only the integration meeting requirements, but also a system-level demonstration in the relevant environment. This will reveal any unknown bugs/defect that could not be discovered until the interaction of the two integrating technologies was observed in the system environment.
<b>SYNTACTIC</b>	<b>7</b>	The integration of technologies has been <b>Verified and Validated</b> and an acquisition/insertion decision can be made.	IRL 7 represents a significant step beyond IRL 6; the integration has to work from a technical perspective, but also from a requirements perspective. IRL 7 represents the integration meeting requirements such as performance, throughput, and reliability.
	<b>6</b>	The integrating technologies can <b>Accept, Translate, and Structure Information</b> for its intended application.	IRL 6 is the highest technical level to be achieved, it includes the ability to not only control integration, but specify what information to exchange, unit labels to specify what the information is, and the ability to translate from a foreign data structure to a local one.
	<b>5</b>	There is sufficient <b>Control</b> between technologies necessary to establish, manage, and terminate the integration.	IRL 5 simply denotes the ability of one or more of the integrating technologies to control the integration itself; this includes establishing, maintaining, and terminating.
	<b>4</b>	There is sufficient detail in the <b>Quality and Assurance</b> of the integration between technologies.	Many technology integration failures never progress past IRL 3, due to the assumption that if two technologies can exchange information successfully, then they are fully integrated. IRL 4 goes beyond simple data exchange and requires that the data sent is the data received and there exists a mechanism for checking it.
<b>SEMANTIC</b>	<b>3</b>	There is <b>Compatibility</b> (i.e. common language) between technologies to orderly and efficiently integrate and interact.	IRL 3 represents the minimum required level to provide successful integration. This means that the two technologies are able to not only influence each other, but also communicate interpretable data. IRL 3 represents the first tangible step in the maturity process.
	<b>2</b>	There is some level of specificity to characterize the <b>Interaction</b> (i.e. ability to influence) between technologies through their interface.	Once a medium has been defined, a "signaling" method must be selected such that two integrating technologies are able to influence each other over that medium. Since IRL 2 represents the ability of two technologies to influence each other over a given medium, this represents integration proof-of-concept.
	<b>1</b>	An <b>Interface</b> between technologies has been identified with sufficient detail to allow characterization of the relationship.	This is the lowest level of integration readiness and describes the selection of a medium for integration.

IRL is a systematic measurement of the interfacing of compatible interactions for various technologies and the consistent comparison of the maturity between integration points. For further clarification, the nine levels of IRL presented in Table 1 can be understood as having three stages of integration definition: semantic, syntactic, and pragmatic. Semantics is about relating meaning with respects to clarity and differentiation. Thus IRL 1-3 are considered fundamental to describing what we define as the three principles of integration: interface, interaction, and compatibility. We contend that these three principles are what define the subsistence of an integration effort. The next stage is Syntactic, which is defined as a conformance to rules. Thus

IRLs 4-7 are about assurance that an integration effort is in compliance with specifications. The final stage is Pragmatic, which relates to practical considerations. Thus, IRLs 8-9 are about the assertion of the application of an integration effort.

With the ability to assess both the technologies and integration elements along a numerical maturation scale, the next challenge was to develop a metric that could assess the maturity of the entire system under development. Therefore, the SRL has been described using a normalized matrix of pair-wise comparisons of TRLs and IRLs for any system under development could yield a measure of system maturity (Sauser et al., 2008b). The rationale behind the SRL is that in the development lifecycle, one would be interested in addressing the following considerations:

- Quantifying how a specific technology is being integrated with every other technology to develop the system.
- Providing a system-wide measurement of readiness.

Under this method, TRL evaluations for each technology and IRL evaluations of each integration are combined using matrix mathematics (explained in detail later) to produce a comprehensive assessment where each technology within the system is weighted according to all of its integrations and then rolled up to a system level. It is important to emphasize that the SRL is not a quantitatively defined rating system, but is instead an analytical combination of the TRL and IRL scales. In others words, the SRL output is purely a function of the TRL and IRL inputs.

Imperative to the development of the SRL have been the supporting methodologies for using the SRL in the practice of systems development and acquisition. Thus, SysDML in conjunction with the US Navy PMS 420/SPAWAR and Northrop Grumman have incorporated SRL into an approach for the assessment of system maturity, as described in this report. While readiness is defined as a scale, maturity is defined as the practices that support the development **(or maturation) of a system's readiness**.

Therefore, SRL is more than purely a qualitative assessment. It requires the user to define the element level contributions of the multiple technologies and integrations that make up the system. In this way, it allows managers to evaluate system development in real-time and take proactive measures by examining the status of all elements of the system simultaneously. Furthermore, the methodology is adaptive to use on an array of system engineering development efforts and can also be applied as a predictive tool for technology insertion trade studies and analysis.

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### 3.1 SRL CALCULATION

Under this method, the evaluation of technology using TRL and the evaluation of each integration using IRL are combined via a set of mathematical formulas (explained in

detail later) to produce an integrated assessment where each technology within the system is weighted according to all of its integrations and then calculated at a system level. It is important to emphasize that the SRL is not a quantitatively defined rating system, but is instead an analytical combination of the TRL and IRL scales. A fundamental assertion in the calculation of the SRL is our interpretation and use of these inputs. We assert that the TRL and IRL inputs are purely data inputs into the SRL calculation, and we do not assert any specific form of numerical scale, i.e. nominal, ordinal, interval, or ratio. Thus, to assert a form of scale-conversion on the inputs prepositions that the origin of the data type is known or natural. Lord (1953) describes this as, “**the numbers do not know where they came from.**” Likewise, Gaito (1980) states that there are some fundamental misconception in the conversion or use of data for mathematical purposes. He explains that the four scales or measurement levels introduced by Stevens (1946) **are a** “confusion of measurement theory and statistical theory” (Gaito, 1980). Since TRL and IRL are scales of non-natural origin, their interpretations of forms of scale are also interpretable by the user of the data. Thus, we make 9=9, 8=8, 7=7, etc. This conversion is justifiable if the conversion does not alter the scale (e.g. 8 does not become more important than 9 or 7 less important than 6) (Shah and Madden, 2004, Akritas, 1990). As discussed in Sauser, et al. (Sauser et al., 2008b) and Magnaye, et al. (Magnaye et al., 2010), the use of scale data in mathematically assessing progress or status without scale-conversion is not without precedence, i.e. Grade Point Average (GPA), Analytical Hierarchy Process (AHP) and Failure Mode Effects and Criticality Analysis (FMECA). In continued research by the SysDML, the degree of variation is been investigated that will allow for the TRL, IRL, and SRL values to move from ordinal to nominal data.

The computation of the SRL is a function of the TRL and IRL matrices:

- Matrix **TRL** provides a blueprint of the state of the system with respect to the readiness of its technologies. **TRL**, defined as a vector with ***n*** entries, is defined in Equation 1, where  $TRL_i$  is the TRL of technology ***i***.

$$[TRL]_{n \times 1} = \begin{bmatrix} TRL_1 \\ TRL_2 \\ \dots \\ TRL_n \end{bmatrix}$$

- Matrix **IRL** illustrates how the different technologies are integrated with each other from a system perspective. For a system with ***n*** technologies, [IRL] is defined in Equation 2, where  $IRL_{ij}$  is the IRL between technologies ***i*** and ***j***. The hypothetical integration of a technology ***i*** to itself is denoted by  $IRL_{ii}$ .

$$[IRL]_{n \times n} = \begin{bmatrix} IRL_{11} & IRL_{12} & \dots & IRL_{1n} \\ IRL_{21} & IRL_{22} & \dots & IRL_{2n} \\ \dots & \dots & \dots & \dots \\ IRL_{n1} & IRL_{n2} & \dots & IRL_{nn} \end{bmatrix}$$

Briefly stated, the IRL matrix is obtained as a symmetric square matrix (of size  $n \times n$ ) of all possible integrations between any two technologies in the system. For technology integration to itself, perfect integration is assumed ( $IRL = 9$ ) while an IRL of zero is used when there is no integration between two elements. On the other hand, the vector TRL defines the readiness level of each of the technologies in the system. The calculation of the SRL has also gone through a series of refinements and the most recent thorough discussion has been presented by Sauser et al. (2008a). As a result of this research another minor modification to the SRL calculation is the re-naming the SRL vector (i.e.  $SRL_i$ ) to  $ITRL_i$ .  $ITRL_i$  indicates the maturity of technology  $i$  with its integrations considered. With a system comprised of  $n$  technologies, it is mathematically described as

$$[ITRL] = \begin{bmatrix} ITRL_1 \\ ITRL_2 \\ \dots \\ ITRL_n \end{bmatrix} = \begin{bmatrix} (IRL_{11}TRL_1 + IRL_{12}TRL_2 + \dots + IRL_{1n}TRL_n) / m_1 \\ (IRL_{21}TRL_1 + IRL_{22}TRL_2 + \dots + IRL_{2n}TRL_n) / m_2 \\ \dots \\ (IRL_{n1}TRL_1 + IRL_{n2}TRL_2 + \dots + IRL_{nn}TRL_n) / m_n \end{bmatrix} \quad \text{where } IRL_{ij} = IRL_{ji}$$

Where  $m_i$  is the number of integrations with technology  $i$  plus its integration to itself. With the ability to assess both the technologies and integration elements along a numerical maturation scale, the next challenge was to develop a metric that could assess the maturity of the entire system under development. Therefore, the SysDML has described how using a normalized matrix of pair-wise comparisons of TRLs and IRLs for any system under development could yield a measure of system maturity. SRL is then calculated as

$$SRL = \frac{ITRL_1 + ITRL_2 + \dots + ITRL_n}{n}$$

We will explain in section 4.1.2 SRL MAPPING TO DEVELOPMENT ACTIVITIES/STATUS how the data from the SRL method is best interpreted.

### 3.2 SRL ALTERNATIVES

While we have investigated multiple ways of formulating an SRL from TRL and IRL inputs, we never contend that the SRL calculation just presented is the only way to

effectively utilize TRL and IRL data. We have found that this method is sufficient and has shown great applicability and insight to developmental risks in systems engineering. That said, there are alternative approaches to using TRL and IRL data to formulate a SRL. With that, as part of this research we describe a different approach to determining the SRL that extends the method proposed by Ramirez-Marquez and Sauser (2009) in their paper "System Development Planning via System Maturity Optimization." As stated, the SRL index incorporates both the TRL and IRL in order to provide a measure of the maturity of a system. All these measures, IRL, TRL and SRL, take integer values between [0,9], in their standard versions, or real values between [0,1] in their normalized versions. The idea behind SRL is to use it as a decision support approach, via resource allocation, in order to assess the system's developmental maturity and lifecycle position.

The goal of this sub-task was to look at an alternative way of determining the SRL index using tropical geometry, in particular min-plus algebra. This algebra is an attractive tool for computing SRL when a fundamental premise is that a system cannot be "more ready" than the "less ready" of its sub-systems; this is what min-plus algebra will reflect when applied to this particular situation. Throughout all the calculations in the presentation of the min-plus algebra we use the normalized versions of the SRL, TRL and IRL, for simplicity purposes.

We show two particular cases when there are  $n$  technologies with IRL equal to zero (i.e. the technologies are fully disconnected) and when the  $n$  technologies are fully connected (i.e. IRL=9 or 1 in its normalize version). We provide a short introduction to min-plus algebra as well as its application to the cases described above. Lastly we present an example using only two technologies for the cases when IRL=0, IRL=9 and when the two technologies have the same fixed level of technology.

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### 3.2.1 MIN-PLUS ALGEBRA

In order to provide a better understanding of our computations in further sections we start with a short overview of the min-plus algebra. For a more comprehensive review of the min-plus algebra the reader is referred to Shutter and Moor (1997) and Cohen et al. (1999); some applications can be found in Heidesgott et al. (2006) and Mikhalkin (2006).

A min-plus algebra is a semi-ring with the algebraic structure  $\mathbf{P}_{\min} = (\mathfrak{R}_{\min}, \oplus', \otimes, e, \varepsilon')$ , where,

- $e=0$
- $\varepsilon' = \infty$
- $\mathfrak{R}_{\min} = \mathfrak{R}_n \cup \{\varepsilon'\}$ ,  $\mathfrak{R}$  are the real numbers.
- $\oplus' : \mathfrak{R}_{\min} \times \mathfrak{R}_{\min} \rightarrow \mathfrak{R}_{\min}$ , such that, given  $a, b \in \mathfrak{R}_{\min}$

$$a \oplus b = \min \{a, b\}$$

$$\bullet \otimes : \mathfrak{R}_{\min} \times \mathfrak{R}_{\min} \rightarrow \mathfrak{R}_{\min}, \text{ such that, given } a, b \in \mathfrak{R}_{\min} \text{ i.e. } n$$

$$a \otimes b = a + b$$

The operation  $\oplus$  and  $\otimes$  have several algebraic properties such as associativity, commutativity, distributivity of  $\otimes$  over  $\oplus$ ; among others.

For matrices  $A \in \mathfrak{R}_{\min}^{n \times p}$  and  $B \in \mathfrak{R}_{\min}^{p \times m}$ , then matrix product  $A \otimes B$  is defined by

$$[A \otimes B]_{i \ k} = \bigoplus_{j=1}^p a_{i \ j} \otimes b_{j \ k}$$

$$= \min_{j \in \underline{p}} \{a_{i \ j} + b_{j \ k}\}$$

for  $i \in \underline{n}$  and  $k \in \underline{m}$ . Note that  $A \otimes B \in \mathfrak{R}_{\min}^{n \times m}$ . This is just like in the regular linear algebra with "+" replaced by "min" and "x" by "+".

### 3.2.2 n TECHNOLOGIES WITH $IRL=0$ IN THE MIN-PLUS SENSE

In this section we present a different procedure for computing the SRL. Although the procedure looks almost the same than the one presented in section 3.2.1, the computations and the results will be different due to the use of the min-plus algebra. Let us start by computing the vector  $y = [I \ R] [T \ R] L$ , where  $[TLR] = [k_1 \ k_2 \ \dots \ k_n]^T$ .

$$y = [I \ R] [T \ R] L$$

$$= I_n k$$

$$= \begin{bmatrix} \min \{1 + k_1, k_2, \dots, k_n\} \\ \min \{k_1, 1 + k_2, \dots, k_n\} \\ \vdots \\ \min \{k_1, k_2, \dots, 1 + k_n\} \end{bmatrix}$$

We now define the SRL as the  $l_2$ -norm of  $y$  in the min-plus sense. i.e.

$$SRL = |y|^2 = \bigoplus_{i=1}^n y_i \otimes y_i$$

Therefore, for  $n$  Technologies with  $IRL=0$  the SRL is given by

$$SRL = \min \{2 \min (1 + k_1, k_2, \dots, k_n), \dots, 2 \min (k_1, k_2, \dots, 1 + k_n)\}$$

$$= 2 \min \{\min (1 + k_1, k_2, \dots, k_n), \dots, \min (k_1, k_2, \dots, 1 + k_n)\}$$

$$= 2 \min(k_1, k_2, \dots, k_n)$$

### 3.2.3 $n$ TECHNOLOGIES WITH $IRL=9$ IN THE MIN-PLUS SENSE

In the case where we have  $n$  technologies with  $IRL=9$ , we found, in section 3.2.2, that the  $[IRL]$  was given by a matrix having all its elements equal to 1. Therefore, by setting  $[TLR]=[k_1 \ k_2 \ \dots \ k_n]^T$ , we get that the vector  $y$  is given by the following expression.

$$\begin{aligned}
 y &= [I \ R]^{-1} [T \ R] L \\
 &= \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & 1 & 1 \end{pmatrix} \begin{bmatrix} k_1 \\ k_2 \\ \vdots \\ k_n \end{bmatrix} \\
 &= \begin{bmatrix} \min\{1+k_1, 1+k_2, \dots, 1+k_n\} \\ \min\{1+k_1, 1+k_2, \dots, 1+k_n\} \\ \vdots \\ \min\{1+k_1, 1+k_2, \dots, 1+k_n\} \end{bmatrix}
 \end{aligned}$$

Thus,

$$SRL = |y|^2 = \bigoplus_{i=1}^n y_i \otimes y_i = 2 + 2 \min\{k_1, k_2, \dots, k_n\}$$

Note that equations (11) and (15) suggest that in this case (i.e. in the min-plus sense), having  $n$  technologies with  $IRL=0$  or  $IRL=9$  will make a difference, in comparison to the case presented in sections 3.2.1 and 3.2.3.

### 3.2.4 MIN-PLUS METHOD IN GENERAL

Therefore, by setting  $[TLR]=[k_1 \ k_2 \ \dots \ k_n]^T$ , we get that the vector  $y$  is given by the following expression.

$$\begin{aligned}
 y &= [I \ R]^{-1} [T \ R] L \\
 &= \begin{pmatrix} 1 & a_{1,2} & \dots & a_{1,n} \\ a_{2,1} & 1 & \dots & a_{2,n} \\ M & M & O & M \\ a_{n,1} & a_{n,2} & \dots & a_{n,n} \end{pmatrix} \begin{bmatrix} k_1 \\ k_2 \\ M \\ k_n \end{bmatrix} \\
 &= \begin{bmatrix} \min\{1+k_1, a_{1,2}+k_2, \dots, a_{1,n}+k_n\} \\ \min\{a_{2,1}+k_1, 1+k_2, \dots, a_{2,n}+k_n\} \\ M \\ \min\{a_{n,1}+k_1, a_{n,2}+k_2, \dots, 1+k_n\} \end{bmatrix}
 \end{aligned}$$

Thus,

$$SRL = |y|^2 = \bigoplus_{i=1}^n y_i \otimes y_i = 2 \min_{i=1; \dots; n} \{ \min_{j=1; \dots; n} \{ a_{i,j} + k_j \} \}$$

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Therefore, the Min-Plus method gives the result of the minimum of the sum of  $TRL_i$  and the lowest IRL that between Technology i and any other technologies

Note that  $k_j \leq a_{i,j} + k_j \leq 1 + k_j$

$$a_{i,j} + k_j = \begin{cases} k_j & \text{Technology } i \text{ NOT connected to ATLEAST ONE of the technologies} \\ 1 + k_j & \text{Technology } i \text{ MOST MATURELY connected with EVERY other technology} \end{cases}$$

So we have

$$\square \quad SRL = 2 \min_{i=1, \dots, n} \left\{ \min_{j=1, \dots, n} \{a_{i,j} + k_j\} \right\} = \begin{cases} 2 \min(k_1, \dots, k_n) & \text{corresponds to scenario 32 when fully disconnected.} \\ 2 + 2 \min(k_1, \dots, k_n) & \text{corresponds to scenario 33 when fully and most maturely connected.} \end{cases}$$

### 3.2.5 EXAMPLE: TWO TECHNOLOGIES

The following example shows how the model works in the case where the system has only 2 technologies. We discuss three possible scenarios:

- (fully disconnected)  $IRL=0$  among the two technologies.
- (fully connected)  $IRL=9$  among the two technologies.
- The same fixed technology readiness level among the two technologies. i.e.

$$TRL = TRL$$

For any of the three scenarios, let  $[IRL] = \begin{pmatrix} a_1 & a_2 \\ a_2 & a_1 \end{pmatrix}$  and  $[TRL] = \begin{bmatrix} k_1 \\ k_2 \end{bmatrix}$ , then

$$\begin{aligned} y &= [IRL] \otimes [TRL] \\ &= \begin{bmatrix} \min\{a_1 + k_1, a_2 + k_2\} \\ \min\{a_2 + k_1, a_1 + k_2\} \end{bmatrix} \end{aligned}$$

#### 1. (fully disconnected) $IRL=0$ among the two technologies.

If  $a_2 = 0$ , i.e.  $IRL=0$  among technologies, then

$$|y|^2 = \bigoplus_{i=1}^2 y_i \otimes y_i = \min\{2k_2, 2k_1\} = 2 \min\{k_2, k_1\}$$

#### 2. (fully connected) $IRL=9$ among the two technologies.

If  $a_2 \rightarrow a_1$ , then

$$\begin{aligned} |y|^2 &= \bigoplus_{i=1}^2 y_i \otimes y_i = \min\{2 + 2 \min\{2k_1, 2k_2\}, 2 + 2 \min\{k_1, k_2\}\} \\ &= 2 + 2 \min\{k_1, k_2\} \end{aligned}$$

### 3. The same fixed technology readiness level among the two technologies.

If  $k_1 = k_2 = k$ , then

$$\begin{aligned}
 |y|^2 &= \bigoplus_{i=1}^2 y_i \otimes y_i = \min\{2 \min(a_1 + k, a_2 + k), 2 \min(a_1 + k, a_2 + k)\} \\
 &= 2 \min(a_1 + k, a_2 + k) = 2(a_2 + k) = 2a_2 + 2k \\
 |y|^2 &= \bigoplus_{i=1}^2 y_i \otimes y_i = \min\left\{2\left(\frac{a_2}{a_1} + k\right), 2\left(\frac{a_2}{a_1} + k\right)\right\} \\
 &= 2\frac{a_2}{a_1} + 2k
 \end{aligned}$$

□

The following graph shows the system readiness levels for the different technology readiness levels using this equation.

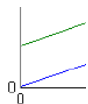


Figure 2: SRLs for the different TRLs using Min-Plus SRL

### 3.2.6 COMPARISON OF SRL TO MIN-PLUS SRL

In this section, we calculated the SRL for two systems that consisted of the same fully mature technologies (all TRL=9), but differ in the following:

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- one with no integration
- the other one is fully connected, and all IRL=9

In our examples we identified some limitation of the SRL for these two systems because the SRL value was the same, and then presented the min-plus method that can solve this problem. However, in these examples we assumed that we had no knowledge of the system architecture but was only looking at the one-to-one relationships. The SRL is intended to be used when the architecture of a system is already known, and an isolated technology is not to be considered part of the system. Under this assumption, the two presented systems are different, the first one would not be considered a system. Therefore, our argument in this case is invalid when considering a complete system architecture. It only tells us that the SRL does not account for the process when an architecture is from unknown to known.

From the general formula for the Min-Plus SRL method, this method calculates the SRL as the minimum of the sum of  $TRL_i$  and the lowest IRL that between Technology  $i$  and any other technologies. The Min-Plus method intends to use the lowest component readiness level as the SRL, through which to find the component whose maturity is lagging the most. However like the SysDML SRL, it still does not tell which TRL is the lowest or which IRL is the lowest. Thus, this method works when the system is fully connected (every technology is connected with any other technologies), and identifies the weakness of maturity with the consideration of TRL and IRL. However, when the system is not fully connected which is more often in reality, we do not know if the weakness is just the TRL or is the combination of TRL and IRL because any non-zero IRL will be eliminated by a zero IRL in the min-plus method. To solve this problem, a simple formula can be used to define SRL as:  $SRL = (\min(TRL_i), \min(IRL_{ij}))$ . Table 2 summarizes the comparison of the two methods.

**Table 2: Comparison of SRL and Min-Plus SRL**

	SDML SRL	Min-Plus
<b>Formula</b>	$ITRL = IRL * TRL$ $SRL = \text{Average}(ITRL_i)$	$y = [IRL] * [TRL]$ $SRL =  y ^2 = \bigoplus_{i=1}^n y_i \otimes y_i = 2 \min_{i=1}^n \{ \min_{j=1}^n \{ a_{i,j} + k_j \} \}$
<b>Risk Orientation</b>	Neutral	Risk-Averse
<b>When to use</b>	The architecture (technology/integration) of a system is known	1. Can be used during the process of figuring out system architecture. 2. Can be used for a known architecture
<b>What it does</b>	Provide results that take into account all the component RLs	Provide result of the minimum of the sum of $TRL_i$ and the lowest IRL that between Technology i and any other technologies.
<b>Give the readiness of a technology with the consideration of all its integrations?</b>	Yes	No
<b>Identify the most immature component?</b>	No, because the result is averaged.	Yes
<b>Manifest the improvement on the other aspects expect the lowest RL?</b>	Yes, the improvement of other aspects contributes to the value of ITRLs/SRL.	No, because it only provides the lowest value.
<b>Identify the lowest TRL?</b>	No	No
<b>Identify the lowest IRL</b>	No	No

## 4 LINKING SRL TO ARCHITECTURE, DEVELOPMENT, MILESTONES, AND COSTS

### 4.1 ALIGNING SRL METHODS WITH ARCHITECTURES

In understanding what the SRL method means to systems engineering architecture, we first must clarify what is meant by maturity and readiness. We distinguish these two terms as: the readiness of a system, technology, or integration implies how ready it is to be deployed on a numeric scale; and maturity is the characterization of the physical development that is quantified by the readiness. Thus, readiness is a scale, and maturity is the definition of each level in the scale. We also distinguish maturity within a system

as having three dimensions: physical, logical, and functional. The TRL, IRL, and SRL are the maturity of the physical representation of a system or its physical architecture. Thus, the first step in applying the SRL Method is to understand the physical system and its representative architecture, which shows the system design broken down into all its constituent elements (i.e., subsystems and components). Likewise, this architecture is supported by its functional and logical representations. With respects to this research, we only focus on the physical architecture. As described in the Technology Readiness Assessment Deskbook: **“The physical architecture includes a representation of the software and hardware ‘products’ necessary to realize the concept. The physical architecture forms the basis for design definition documentation (e.g., specifications, baselines, and the work breakdown structure (WBS))”**. The allocation of the functional definition of the system to **the physical definition of the system completes the “design”** of the system and the definition of its components.

Conversely, a functional definition of an architecture can be mapped (or allocated) to a physical view component. Together these views define the design (model) of the system. The system model becomes the input to the detailed design and fabrication of the physical components that comprise the system. This physical view establishes all of the discrete subsystems and components that are procured or developed to produce the system. It also defines the interfaces between these subsystems and components.

The physical view also identifies the selection of technologies, including both developed and commercial, that will comprise each subsystem or component. In this way, the physical architecture includes a representation of the software and hardware **“components” necessary to realize the system. This physical view then provides a clear definition of the elements of the system that are needed to perform the SRL assessment.**

In brief, a system architecture model is needed to reason about a problem in a scientific way. So to find the bottlenecks and "imperfections" of a system, there is a need for a concise but mighty method of modeling a system of interest. DoDAF provides those models in terms of many models and views. The DoD Architecture Framework (DoDAF) defines a common approach for DoD architecture description, development, presentation, and integration. DoDAF version 2.0 describes four related technical viewpoints of architecture:

1. The Capability Viewpoint (CV) identifies the requirements and delivery of the system.
2. The Operational Viewpoint (OV) identifies what needs to be accomplished and who does it.
3. The Services Viewpoint (SvcV) identifies the services and exchanges in a services oriented architecture.
4. The Systems Viewpoint (SV) relates systems and characteristics to operational needs.

Products within this framework can be associated with the physical architecture. The SvcV and the SV are very closely related. Indeed, they could be considered to be two alternate views of the design/implementation of a system.

The SV represents the traditional physical design of a system, where as the SvcV represents a more modern Service Oriented Architecture (SOA) design of a system. In this manner, the SV captures the information on supporting automated systems, interconnectivity, and other systems functionality in support of operating activities. As **SOA becomes more predominant it can be expected that over time, the DoD's emphasis** on Service Oriented Environment and Cloud Computing may result in the elimination of the SV. Therefore either the SV-1 or the SvcV-1 can be considered the physical design of the system depending on the architectural approach taken by the design team. These views can be considered as complementary design views.

Physical description is captured in several DoDAF products in either the SV or the SvcV model:

- SV(SvcV)-1, Systems Descriptions

With further descriptions to be found in

- SV(SvcV)-2, Systems Flow Descriptions
- SV(SvcV)-3, Systems(Services)-Systems(Services) Matrix
- SV(SvcV)-7, Systems(Services) Measures Matrix

The elements of the target environment can be established by examination of the physical view of the system design. If the program is using a DoDAF structure, this can be accomplished by examination of the SV-1 or SvcV-1 diagram. The components blocks on the diagram represent the elements (components) of the system. These are the candidate items to be reviewed for possible use in the SRL assessment. All of the connectors on the diagram represent interfaces that will be candidates for evaluation as part of the SRL.

To increase the understanding of all system elements, the components included in the derivative models SV(SvcV)-2, SV(SvcV)-3, and SV(SvcV)-7 can be checked to see that all required elements have, in fact, been identified. Another check can be performed by examining the program WBS and comparing the hierarchical development tasks against the elements defined for the SRL methodology. The result of this effort should be a definition of all the elements and interfaces of the system that is very close to the program design and development work definition.

The remainder of this section describes the process for defining all the architectural elements to be modeled in the SRL. This can be performed in five steps:

1. Analyze the architecture to determine all the elements in the system

2. Identify the Critical Technology Elements (CTEs). These will be evaluated and scored in the SRL.
3. Identify the Non-critical Technology Elements (NTEs). These will not be evaluated and scored in the SRL. These elements will not impact the SMA Analysis.
4. Identify the Critical Technology Integrations (CTIs). These will be evaluated and scored in the SRL.
5. Identify the Non-critical Technology Integrations (NTIs). These will not be evaluated and scored in the SRL.

It should be pointed **out that the “system” under development can be at any level of decomposition**. The level of decomposition is determined by the program. It should be at a level of decomposition that the program comfortably feels the major technology components can be identified. At this point we focus on the physical model of the system. When we begin to work in the next step we will use the functional model, and in particular, the allocation of functional to physical. The next step in the SRL architecture definition process is to identify those system components that are CTEs in the development of the system. These will be the elements that will need to be evaluated, rated, and compiled in the SRL assessment. The selection of these CTE components is discussed in the next section of this paper.

Finally, DoDAF 2.0 has added new views and products, in what has been described as a fit for purpose, where emphasis is shifted to the data and artifacts, rather than models. This change suits the prospects of system maturity assessment using system architectures, as criteria and information harvested in a system architecture can be used to aid decision makers when it comes to TRL and IRL. Figures 3 and 4 are extracted from an OV-1, OV-2, and OV-5 product of a DoDAF model which, based on the AV-1 model, explains a Coordinated Land and Sea attack. Figure 3 is captured from IBM Rational Rhapsody, and this is from a DoDAF example where a coordinated Land and Sea Attack is shown. Given this high level description, we navigate to an OV-2, which indicates the key players and the interactions necessary to conduct the corresponding operational activities of OV-5a or OV-5b. The dialog box on the right side contains information regarding the technology that can be used for maturity assessment. The two-column dialog box is highly customizable; a click on edit enables highly customizable information to be added or allocated to support assessment of a technology for a certain level. Figure 3 shows a hypothetical set of criteria required for the evaluation of a technology in the TRL range of 3.

Utilizing the features of OV-2 helps us gain insight into the integration advances of the UAV and COMMS, which is an aircraft and satellite depicted above. The information provided in the dialog box below is set to automatically retrieve the latest information, or point an assessor to the latest data locations which would support the readiness level assessment. Figure 4 is an example that shows the hypothetical criteria required for the assessment of the IRL level of 3.



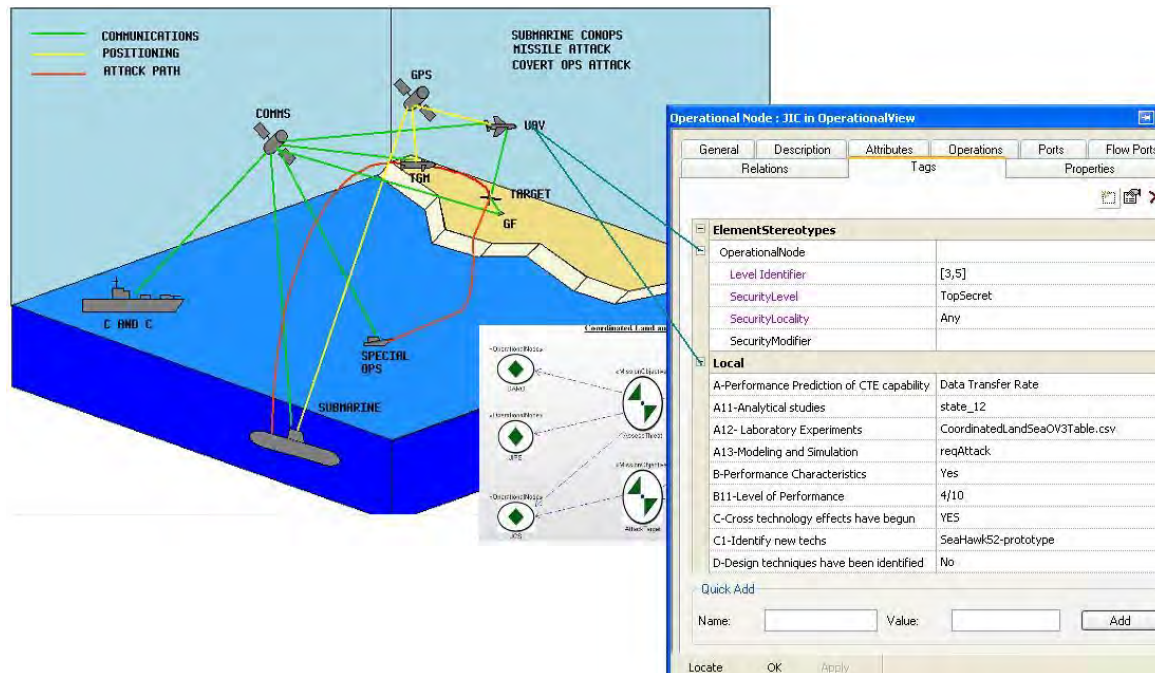


Figure 3: IBM Rational Rhapsody DoDAF Example for TRL Criteria

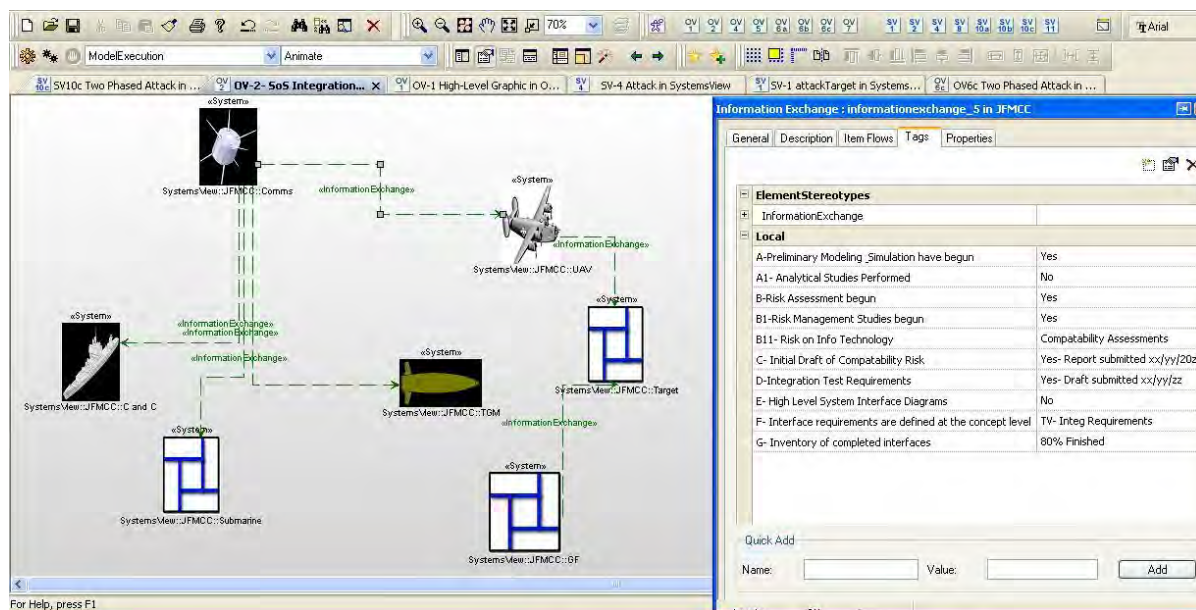


Figure 4: IBM Rational Rhapsody DoDAF Example for IRL Criteria



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## 4.2 MAPPING SRL/ITRL TO DEVELOPMENT ACTIVITIES/STATUS

In defining a mapping of the SRL to developmental activities/status we wanted to make sure that there was enough flexibility in the SRL Method to allow for the values to be correlated or adjusted to varying organizational practices. What we will describe is how it was implemented within PMS420 and supported by Northrop Grumman; although, these same practices have been used in other organizations within Lockheed-Martin and NASA.

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### 4.2.1 TRL/IRL ASSESSMENT

For determining the TRL of a technology, there are methods (e.g. Missile Defense Agency Checklist), processes (e.g. TRA Deskbook), and tools (e.g. AFRL TRL Calculator; Department of Homeland Security (DHS) TRL Calculator). Some of these have become common practice in the DoD, but there is limited guidance on IRL. In conjunction with the nine level IRL already specified, we have developed supporting guidance that further clarifies each IRL. This is detailed in Appendix A and further explained by Sauser, et al. (2010).

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### 4.2.2 SRL/ITRL INTERPRETATION

Aside from the SRL providing an assessment of overall system development, in concert with the ITRL it can also be a guide in prioritizing potential areas that require further **development. That is, if we are considering a “systems-focused approach” to our methodology**, then we cannot evaluate a system based on just a single number, such as the SRL value alone. As illustrated in Figure 3, the ITRLs (technologies with their integration links considered) present a spectrum showing some technologies with their integrations considered whose readiness levels could be in different development phases other than the overall system. While it could be argued that the overall SRL is only as good as the lowest TRL or ITRL, this perspective would also lose sight of even those technologies that are potentially developing faster than the system. In understanding the value of the SRL analysis, we must understand the spectrum of ITRL and its relationship to the SRL. In Figures 5 and 6, we see the same overall system providing a functionality and capability but with different technology and integration options. If we focused on the SRL alone in comparing these two systems, we would not see the influence these options have on the systems development because we would only see a 0.04 difference in the SRL (0.60 to 0.64). In effectively utilizing the SRL method, you have to consider all of the data, i.e. SRL and ITRLs, and use this as better insight into system maturity.

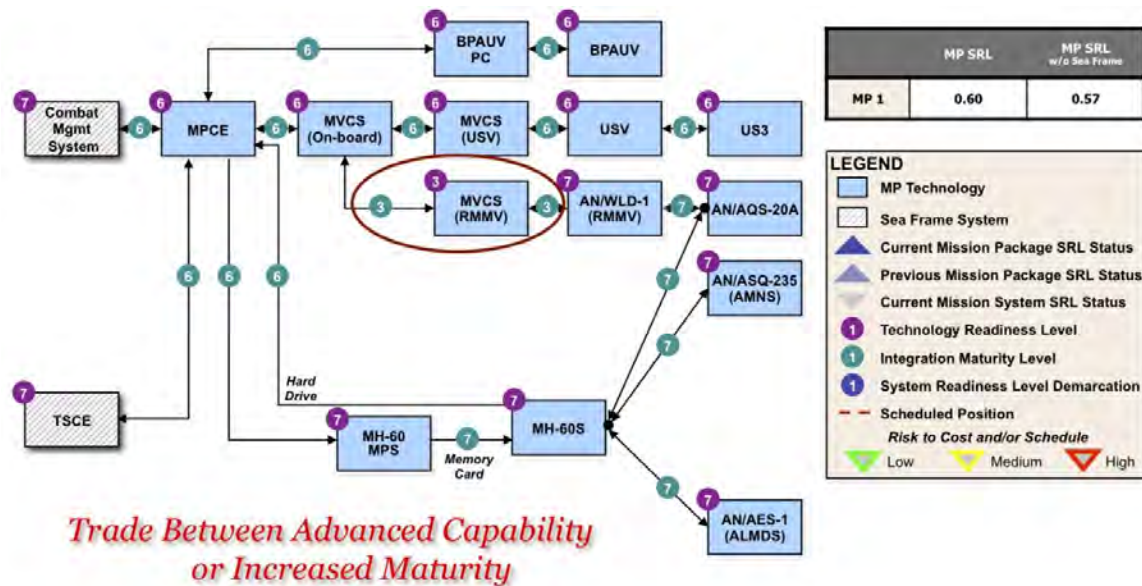


Figure 5: SRL/ITRL Reporting (provided by Northrop Grumman)

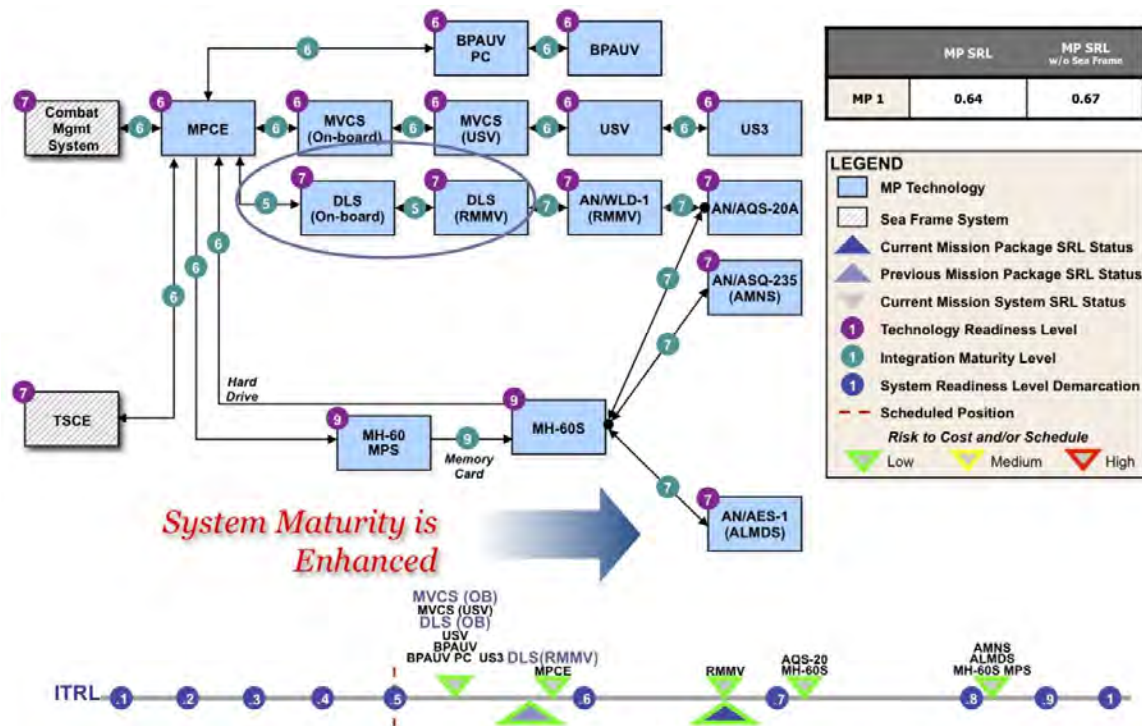


Figure 6: SRL/ITRL Reporting (provided by Northrop Grumman)

### 4.2.3 SRL MAPPING

Despite the utility of calculating a SRL and its supporting ITRLs, without an articulated correlation to qualitative systems engineering practices, it becomes difficult to determine the added value in understanding its implication on the development lifecycle. To address this we have subsequently performed further verification and validation of this approach to other cases in conjunction with system developers from DoD, Lockheed-Martin, NASA, and Northrop Grumman. This work continues and will need extensive validation to provide the level of confidence needed in its practice to make minimal risk decisions. In general, the 0.0-1.0 SRL/ITRL range that allows status to be efficiently mapped to program development maturity is represented in Figure 7. While this mapping indicates distinct numeric values at phase transition points, in practice, we contend that these transitions should be managed within a tolerance of risk acceptance. For example, a SRL/ITRL for Milestone B may have a tolerance of +/- 10%, indicating that an SRL/ITRL value that falls within this tolerance is still acceptable for progressing past Milestone A.

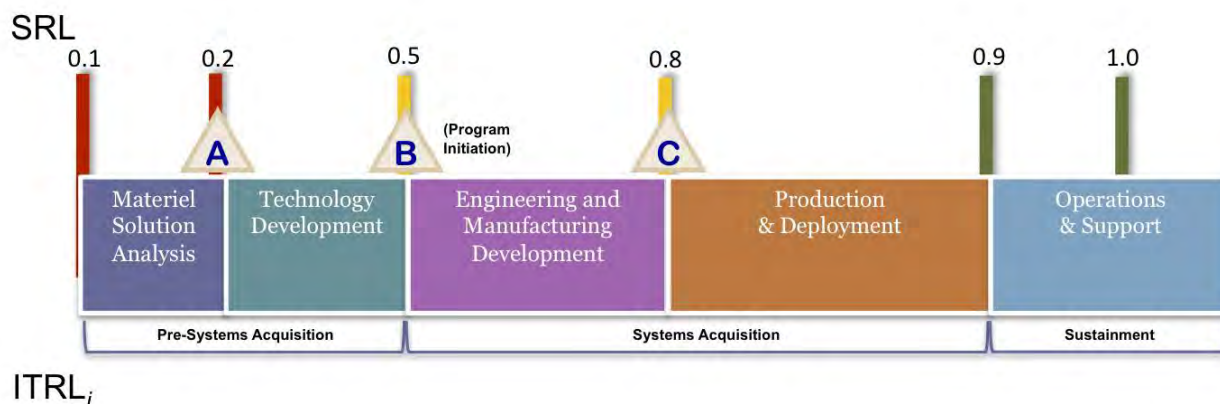


Figure 7: SRL and ITRL Mapped Against DoD Defense Acquisition Lifecycle

### 4.2.4 SRL REPORTING

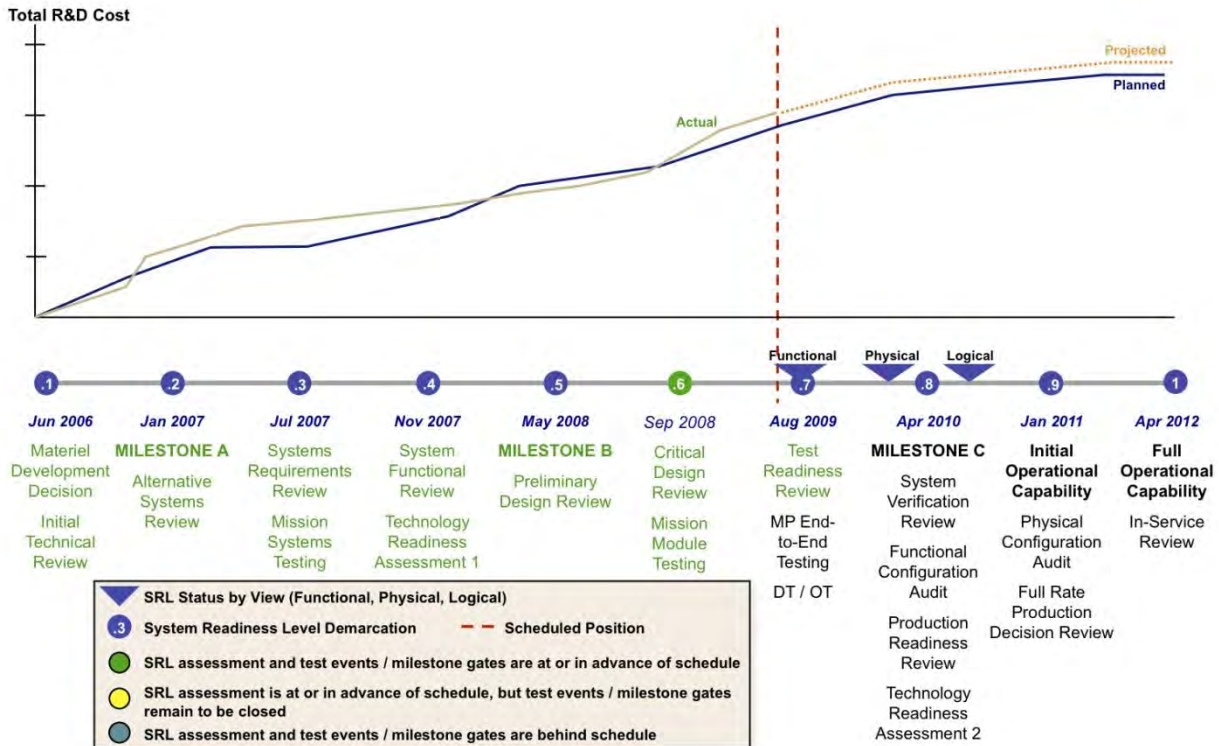
In our development of an SRL method, we strived to maintain a systems-focused approach that would create a metric(s) to address some of the current concerns with the TRL. What resulted was a set of metrics and an approach that can have the following implications on defense acquisition:

- The SRL, ITRL, IRL, and TRL provide an enhanced capability alignment through the identification of specific technology, integration, and system maturities that can be used as a trade-study tool to select the most appropriate technologies and

integrations to obtain the lowest amount of risk, cost, and time and satisfy a given customer need. This can be observed by comparing Figures 5 and 6.

- The SRL Method can improve customer confidence in the acquisition manager by providing a qualification of system maturity in relation to system functionality. It **can also provide improved understanding of the system's mission capabilities** in terms of readiness criteria.
- The SRL/ITRL can provide an assessment of maturity at multiple architectural layers. Any single SRL assessment contains multiple ITRL assessments, which can provide insight into the interdependencies of different sub-functions and how they fit within the larger architecture. This can be observed by comparing Figures 5 and 6.
- The SRL, IRL, and TRL provide common ontology to measure and describe acquisition development, system development and technology-insertion evaluation.
- The IRL reduces the uncertainty involved in integrating a technology into a system and identifies integration as a separate, specific metric.

It also becomes important in how the SRL/ITRL results are reported. Figures 5 and 6 are examples provided by Northrop Grumman in how they report SRL/ITRL to the PMS420, but also SRL data can be reported via planned milestones as shown in Figure 8 (also provided by Northrop Grumman).



**Figure 8: SRL Planned versus Actual Reporting Example (provided by Northrop Grumman)**

## 4.3 LEVERAGING SRL RELATIONSHIPS TO ALLOCATE RESOURCES

SRL was first described in a cost model by Sauser and Ramirez-Marquez (2009) to provide information about which technologies and integrations to advance to which readiness level such that the maturity of the system is maximized based on limited resources made available for system development. In this section we will describe this optimization model as it is applied to the development of a system to illustrate how SRL can be used to plan development. As an example, the systems engineer or program manager who is concerned with utilizing resources allocated for the system can now set development goals such that the maximum amount of system readiness is achieved. In order to execute the development required to have maximum SRL value, it is necessary to know how to utilize the resources optimally. That is, the systems engineering or program manager must determine which of the system components should be matured to what levels so they can allocate the available resources accordingly. We have previously articulated this model in the form of a resource allocation of budget and schedule; described in detail in (Sauser and Ramirez-Marquez, 2009). For this research, we expanded upon this model to utilize the construct of Equivalent System Mass (ESM). Thus, the general mathematical form of this model follows:



Model ESM  $SRL_{max}$   
 Maximize:  $SRL(TRL, IRL)$

Subject to:  $ESM(TRL, IRL) \leq esm$

### 4.3.1 EQUIVALENT SYSTEM MASS

ESM was first defined in 1997 as a metric for comparing technology options for the space life support systems (Drysdale, 2003). It allowed for the tradeoff of mass, volume, power, cooling and crew time based on a single mass value. The fundamental premise was that a mass value could be equated to launch cost (e.g. it costs \$10,000 per pound to launch a payload on the Space Shuttle), thus allowing for the optimization of technology options to achieve mission objectives. It is a common practice in space systems development for mass, as it relates to cost, to be a driver in determining the deployment success of space products (Saleh et al., 2007, Koelle, 2005, Carli and Pablos, 2006). Although cost as an independent variable in the design of space systems has been prevalent throughout the industry for decades, there is a need to shift the emphasis of cost as a driver in the analysis for engineering space systems (Saleh et al., 2007). This was a fundamental motivation for using ESM in lieu of dollar costs for technology development (Drysdale, 2003). ESM allows for cost to become an independent variable and does not have a direct influence on a trade analysis. In summary, ESM provides advantages since cost estimates:

- can be politically sensitive;
- are not generally released;
- do not always include all cost; and
- tend to be complex and dynamic (Drysdale, 2003).

Accordingly, ESM is calculated as:

$$ESM = M + L + V * eqV + P * eqP + C * eqC + CT * D * eqCT$$

where: ESM = equivalent system mass value of the system of interest [kg], M = total mass of the system [kg], L = mass of the materials and spare logistics of the system [kg], V = total pressurized volume of system [m<sup>3</sup>], eqV = mass equivalency factor for the pressurized volume infrastructure [kg/m<sup>3</sup>], P = total power requirement of the system [kWe], eqP = mass equivalency factor for the power generation infrastructure [kg/kWe], C = total cooling requirement of the system [kWth], eqC = mass equivalency factor for the cooling infrastructure [kg/kWth], CT = total crew time requirement for operation and maintenance of the system [CM-h/day], D = duration of the mission segment of interest [day], and eqCT = mass equivalency factor for the crew time support [kg/CM-h]. For a detailed explanation and guidance on ESM see (Levri et al., 2003).

ESM was investigated for this research as mass can be a driver in the development and potential deployment of mission modules as they relate to the efforts of PMS420 and other Littoral Combat Ship efforts. While ESM adds value to the trade analysis of technology options for space missions, it has been noted in those efforts of space systems that it should not be a standalone metric and additional metrics that evaluate the developmental status of a technology would be of added value. More commonly, TRL, as a measure of technology maturity, has been repeatedly cited as a core metric that should be used with ESM (Rodriguez et al., 2004, Russell and Carrasquillo, 2007, Drysdale, 2003, Czupalla et al., 2004). To further enhance the use of TRL with ESM, we created an  $SRL_{\max}$  model that utilized ESM with SRL, i.e.  $ESM\_SRL_{\max}$ .

### 4.3.2 EQUIVALENT SYSTEMS MASS OPTIMIZATION ( $ESM\_SRL_{\max}$ )

The matrices **IRL** and **TRL** of the model contain the decision variables. Each of these variables is integer valued and bounded by  $(IRL_{ij}, 9)$  and  $(TRL_i, 9)$ , respectively. That is, the TRL/IRL for any component cannot be below its current level or above perfect technology or integration development (IRL or TRL = 9). The objective function of Model  $ESM\_SRL_{\max}$  of the system is a function of the decision variables, which dictate how the different levels for both TRL and IRL are improved. The left hand side of the inequality constraint represents the ESM as a function of the improved TRLs and IRLs, and the right hand side indicates the total amount allowance of ESM for the whole system. Since the ESM is an indicator of the needed launch cost, the model tries to maximize the system maturity while remaining under the ESM allowance, thus meeting the cost constraint.

To completely characterize the decision variables, it is necessary to introduce the following transformation:

$$y_i^k = \begin{cases} 1 & \text{If } TRL_i = k \\ 0 & \text{otherwise} \end{cases} \quad \text{and} \quad x_{ij}^k = \begin{cases} 1 & \text{If } IRL_{ij} = k \\ 0 & \text{otherwise} \end{cases} \quad \text{for } k=1, \dots, 9$$

Notice that based on these binary variables, each of the possible normalized TRL and IRL in the system can be obtained as:

$$TRL_i = \frac{\sum_{k=1}^9 k y_i^k}{9} \quad \text{and} \quad IRL_{ij} = \frac{\sum_{k=1}^9 k x_{ij}^k}{9}$$

and  $ITRL_i$  is transformed to:

$$ITRL_i = \frac{1}{m_i} \left( \frac{\sum_{k=1}^9 k x_{i1}^k}{81} + \frac{\sum_{k=1}^9 k x_{i2}^k}{81} + \dots + \frac{\sum_{k=1}^9 k x_{in}^k}{81} + \dots + \frac{\sum_{k=1}^9 k x_{ij}^k}{81} + \dots + \frac{\sum_{k=1}^9 k x_{im}^k}{81} \right)$$

The model belongs to the class of binary, integer-valued, non-linear problems. For example, a system with **6** technologies containing **10** distinct integrations, and assuming all technologies and integrations are at their lowest levels, there can be as many as  $9^{6+10}$

potential solutions to the model. Evaluating each possible solution is prohibitive, so to generate a more timely optimal solution, a meta-heuristic approach developed by Ramirez-Marquez and Rocco (2008) is applied to solve the optimization model. This approach, called Probabilistic Solution Discovery Algorithm (PSDA), has the capability of producing quasi-optimal solutions in a relatively short period of time. However, it must be mentioned that the results cannot be proven to be the optimal solution. This is because by taking a probabilistic approach, the algorithm can only select subsets of the entire feasible set from which to find a solution. Every time the algorithm is run, a different subset is selected. Nevertheless, prior tests have indicated that PSDA results tend to be better than results from alternative meta-heuristic approaches (Ramirez-Marquez and Rocco, 2007).

As used in the solution of the maximization problem, after the algorithm is initialized, it follows three inter-related steps:

- Strategy Development – a Monte Carlo simulation is used to identify to what potential TRL or IRL levels the technologies and links can be advanced or matured;
- Analysis – each potential solution is analyzed by calculating its associated SRL and ESM;
- Selection – through an evolutionary optimization technique, a new optimal set of technologies and integration links (with their corresponding TRLs and IRLs is chosen (based on the SRL and ESM values).

During Strategy Development, based on the probabilities defined by vectors  $\gamma_{iu}$  and  $\gamma_{iju}$ , the simulation is used to generate a specified number (defined by  $V$ ) of potential designs,  $\mathbf{TRL}_u^v$  and  $\mathbf{IRL}_u^v$  ( $v=1, \dots, V$ ). For each technology  $i$ ,  $g_{iu}^k$  (the  $k^{\text{th}}$  element of vector  $\gamma_{iu}$ ) defines the probability that at cycle  $u$ , the TRL of such a technology will increase its current readiness to level  $k$  (i.e.  $g_{iu}^k = P(y_i^k = 1)$ ). Similarly,  $g_{iju}^k$  defines the probability that at cycle  $u$ , the IRL between the  $i^{\text{th}}$  and  $j^{\text{th}}$  technologies will increase its actual readiness to level  $k$  (i.e.  $g_{iju}^k = P(x_{ij}^k = 1)$ ). This step also contains the stopping rules of the algorithm. In essence, the first rule, which is used in this paper, allows the user to set a specific number of cycles. The second rule dictates the algorithm to be stopped once both vector  $\gamma_{iu}$  and  $\gamma_{iju}$  **can no longer be updated (i.e. all initial “appearance” probabilities are either zero or one)**. In the context of this algorithm a cycle is understood as every time the value  $u$  is updated.

The second step, Solution Analysis, implements the approach discussed in Sauser et al. (2008a) and previously summarized to obtain the SRL, and the ESM of the development associated with each of the potential system design,  $\mathbf{TRL}_u^v$  and  $\mathbf{IRL}_u^v$ . The final step in the algorithm penalizes the SRL of the potential designs generated in cycle  $u$  whenever they violate the ESM constraints. The solutions are then ranked in decreasing order of magnitude with respect to the penalized SRL. Then, the best of these solutions is stored



in set  $K$  and finally, a subset of size  $S$  of the ranked feasible solutions, is used to update the probabilities defined by the vectors  $\gamma_{iu}$  and  $\gamma_{ju}$ . These new vectors are re-evaluated in Step 1 to check for termination or for solution discovery. Finally, when the prescribed number of cycles has been reached, the best solution in set  $K$  is chosen as the optimal system design.

### 4.3.3 EXAMPLE: RESULTS AND DISCUSSION

There can be several technology options proposed to address any system solution. Each of the technology options presents various design and development challenges, e.g. maturity, mass, budget. For our simulation we will run the  $ESM_{SRL_{max}}$ , demonstrating the insights that the addition of SRL to the calculation of ESM can have on making more informed development decisions. We will demonstrate this using two nonspecific systems with variations in three technology options (i.e. Technologies 3, 4, and 6) and thus their ESM. These systems have six technologies containing ten distinct integrations; we will call them *System X* and *Systems Y*. We could think of these systems as delivering the same capability but with different technology options. Tables 3 and 4 show the TRL and IRL values and Tables 5 and 6 show the ESM values of *Systems X* and *Y*.

**Table 3: Readiness Levels of *System X***

Technology			TRL
Technology 1			5
Technology 2			4
Technology 3			5
Technology 4			4
Technology 5			5
Technology 6			6
Integration	IRL	Integration	IRL
1,2	4	2,6	4
1,5	5	3,4	4
2,3	4	3,5	5
2,4	4	4,6	6
2,5	4	5,6	5

**Table 4: Readiness Levels for *Systems Y***

Technology			TRL
Technology 1			5
Technology 2			4
Technology 3			7
Technology 4			5
Technology 5			5
Technology 6			8
Integration	IRL	Integration	IRL
1,2	4	2,6	4
1,5	5	3,4	4
2,3	4	3,5	5
2,4	4	4,6	6
2,5	4	5,6	5

Based on the current readiness levels of its technologies and integration links as shown in Tables 3 and 4, **System X** would yield a SRL of 0.39, and **System Y** would yield a SRL of 0.33. Referring to Figure 7, these values indicate that both of these system scenarios should be in **Phase A: Concept & Technology Development**.

Tables 5, 6, and 7 show the ESM of each component (technology or integration) at different maturity levels. For example, to mature Technology 1 from TRL of 1 to 9 **Systems X's** ESM is estimated to rise from 2,743 to 3,234 kgs. At their current TRLs and IRLs, the overall ESM for **System X** is 43,273 and 59,079 for **System Y**. In order to fully mature all the technology and integration elements, **System X** is allowed a maximum ESM of 44,876 and **System Y** of 60,122 without any budgetary tolerances. These values are obtained as the sum of the ESM values when all TRLs and IRLs are equal to 9.

**Table 5: Cumulative ESM for Technology Elements against TRL (Current TRLs in Bold) - System X**

TRL	Technology					
	1	2	3	4	5	6
1	2743	2302	3350	1302	2926	17139
2	2835	2551	3489	1385	3074	18499
3	2986	2633	3765	1389	3273	19778
4	3058	<b>2767</b>	3897	<b>1462</b>	3356	19864
5	<b>3131</b>	2836	<b>3926</b>	1498	<b>3476</b>	20466
6	3212	2873	4004	1510	3526	<b>20988</b>
7	3230	2898	4044	1521	3562	21357
8	3233	2907	4096	1536	3580	21521
9	3234	2911	4111	1538	3597	21610

**Table 6: Cumulative ESM for Technology Elements against TRL (Current TRLs in Bold) - System Y**

TRL	Technology					
	1	2	3	4	5	6
1	2743	2302	6413	1956	2926	25635
2	2835	2551	6679	2081	3074	27669
3	2986	2633	7208	2087	3273	29582
4	3058	<b>2767</b>	7460	2197	3356	29711
5	<b>3131</b>	2836	7516	<b>2251</b>	<b>3476</b>	30611
6	3212	2873	7665	2269	3526	31392
7	3230	2898	<b>7742</b>	2285	3562	31944
8	3233	2907	7841	2308	3580	<b>32189</b>
9	3234	2911	7870	2311	3597	32322

**Table 7: Cumulative ESM for Integration Elements against IRL (current IRLs in bold)**

IRL	Integration									
	1,2	1,5	2,3	2,4	2,5	2,6	3,4	3,5	4,6	5,6
1	624	963	1352	371	689	757	703	241	279	543
2	679	1017	1477	395	701	846	765	260	294	547
3	693	1088	1514	417	729	896	805	276	296	585
4	<b>729</b>	1090	<b>1540</b>	<b>431</b>	<b>744</b>	<b>943</b>	<b>847</b>	279	300	589
5	749	<b>1092</b>	1565	438	763	956	881	<b>290</b>	302	<b>604</b>
6	761	1116	1581	441	773	972	901	293	<b>303</b>	608
7	770	1130	1597	442	778	973	905	294	308	612
8	776	1136	1600	446	784	978	908	297	310	613
9	779	1144	1601	448	787	979	914	299	312	614

To further explain the model, we will describe a situation where, for example, the program manager wants to show the customer to which maturity level or development stage they can take a system if they are given various ESM allowances. For simplicity we will focus on **System X** and then compare the results of the two systems. In order to answer this, the PSDA optimization model computed the respective maximum SRL values when 20%, 40%, 60%, 80% and all of the ESM allowance is allocated. The results are shown in Table 8. For example, when the ESM is allowed to increase from 43,273 (current value) to 43,901 (utilizing around 40% of the remaining allowable increase in ESM), the SRL can be increased from 0.33 to 0.76. This takes **System X** from **Phase A** to a state where it would soon transition from **Phase B: Preliminary Design & Technology Completion** to **Phase C: Final Design & Fabrication**. In addition, the development plan which can achieve the SRL value of 0.76 when 40% of the incremental ESM is allocated also shows that the subsystems which are based on each technology element reach their respective maturity levels as shown in Table 8. The 40% case shows that of the six subsystems, three are ahead (ITRL<sub>1,4,6</sub>), two are slightly behind (ITRL<sub>2,5</sub>) and one, (ITRL<sub>3</sub>) is close to the same level as that of the whole system. This insight can become useful when the maturity levels are associated with systems engineering activities; hence, the spectrum of ITRL<sub>i</sub>'s **can indicate levels of variation in** the systems engineering activities which are needed to mature the entire system.

While the SRL scale can have value for overall planning, one can assess the developmental maturity of each technology and corresponding integrations based on the ESM allowances using Model ESM\_SRL<sub>max</sub>. Table 9 illustrates the associated TRL and IRL levels obtained from the optimal solution for each of the cases considered. This is very important to understanding how the optimization approach can influence the developmental maturity of the individual technologies and integrations. That is, the optimal TRL and IRL levels obtained from the model becomes a guidance tool for the systems engineering manager to better understand how the ESM allowances are impacting maturity of development. Table 9 also indicates that for ALS, an 80% ESM allowance still would not ensure a fully mature system because Technology 6 and two of the IRLs (2,3; 2,6) are not completely matured. The technology involved is the food processing component and the integration elements are the ones that connect the crew

habitat to it as well as to the water processing facility. Unless these can be feasibly matured in space, the system cannot be launched.

It must be pointed out that the design solutions in Table 9 are calculated using the budgeted incremental ESM. However, the solution for each increasing amount of allocated ESM is not dependent on the values of the readiness levels calculated for the preceding lower amount of ESM allocation. That is, the algorithm does not go sequentially from 20% to 40% and so on, such that 20% automatically corresponds to year 1 and 40% to year 2. Rather, what the solution shows is that if a certain % is allocated, the corresponding technologies and integrations can be matured to such levels as indicated. It is up to the decision makers to allocate a budget for any given year and plan the development based on the available budget. This is the reason why Technology 4 can be matured to level 9 under 20% and 40% ESM allowance, whereas it is only matured to level 8 under 60% ESM allowance. However, if a time-related sequential design solution is desired, say for 5 years, a sequential orderly solution can be achieved by following a recursive manner of utilizing the ESM\_SRL<sub>max</sub> model. For example, in order to get an incremental design solution for 20% and 40% ESM allowances corresponding to years 1 and 2 respectively, first execute the model to get the design solution for the 20% scenario then, allocate another 20% for year 2 and re-run the model. That is, when a TRL or IRL has already been achieved for a particular element, it can no longer be de-matured just to follow the prescribed solution from the algorithm. Thus, for the 60% scenario, Technology 4 must stay at TRL 9 and not revert back to 8 as a practical matter.

When we compare **System X** and **Y** we can see the insights of adding the SRL with ESM in making more informed development decisions (see Tables 8-11). The comparison of the best solutions with ESM allowance for the ITRL and SRL (Tables 8 and 10) of the two scenarios does show as much significance as does the best design solution for every increase in ESM allowance (Tables 9 and 11). By comparing the design solutions, we can observe noticeable variation even in technologies and integrations that were not directly related to the varying technologies options (Technologies 3, 4, and 6), which signify the interrelationship among the technologies. For example, though we kept the IRLs constant, the recommended design solution for the integration between technology 1 and 2 is noticeably different. While we kept the IRL estimates constant in the two scenarios, integration is where we are observing the most variance in design solution. Therefore, while the ESM of **System Y** is much higher than that of **System X**, there may be other confounding factors that influence the selection of technology options related to technology and integration maturity and their relationship to ESM.

**Table 8: Best Solution for ESM Increase Allowance – *System X***

Case	ITRL <sub>1</sub>	ITRL <sub>2</sub>	ITRL <sub>3</sub>	ITRL <sub>4</sub>	ITRL <sub>5</sub>	ITRL <sub>6</sub>	SRL	ESM
Current	0.35	0.28	0.31	0.33	0.35	0.37	0.33	43273
20%	0.50	0.46	0.47	0.56	0.50	0.68	0.53	43579
40%	0.81	0.69	0.75	0.79	0.68	0.83	0.76	43901
60%	0.96	0.78	0.89	0.81	0.85	0.81	0.85	44221
80%	1.00	0.90	0.97	0.92	0.93	0.86	0.93	44249
100%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	44876

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**Table 9: Best Design Solution for Every Increase in ESM Allowance – System X**

ESM Allowance	Technology						Integration									
	1	2	3	4	5	6	1,2	1,5	2,3	2,4	2,5	2,6	3,4	3,5	4,6	5,6
Current	5	4	5	4	5	6	4	5	4	4	4	4	4	5	6	5
20%	5	4	5	9	7	6	7	7	4	7	4	7	4	8	9	8
40%	5	9	5	9	9	6	9	8	5	9	7	7	8	9	9	8
60%	8	9	9	8	9	6	9	9	7	7	7	7	8	9	9	8
80%	9	9	9	9	9	6	9	9	8	9	9	7	9	9	9	9
100%	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9

**Table 10: Best Solution for ESM Increase Allowance – System Y**

Case	ITRL <sub>1</sub>	ITRL <sub>2</sub>	ITRL <sub>3</sub>	ITRL <sub>4</sub>	ITRL <sub>5</sub>	ITRL <sub>6</sub>	SRL	ESM
Current	0.35	0.32	0.38	0.42	0.40	0.44	0.39	59079
20%	0.42	0.43	0.55	0.65	0.58	0.72	0.56	59279
40%	0.54	0.57	0.64	0.71	0.66	0.87	0.67	59493
60%	0.81	0.73	0.83	0.89	0.78	0.97	0.84	59705
80%	1.00	0.94	0.94	0.92	0.93	0.97	0.95	59863
100%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	60122

**Table 11: Best Design Solution for Every Increase in ESM Allowance – System Y**

ESM Allowance	Technology						Integration									
	1	2	3	4	5	6	1,2	1,5	2,3	2,4	2,5	2,6	3,4	3,5	4,6	5,6
Current	5	4	7	5	5	8	4	5	4	4	4	4	4	5	6	5
20%	5	4	7	9	8	8	4	5	4	7	4	4	4	8	9	8
40%	5	7	7	9	9	8	6	5	4	7	4	7	4	9	9	9
60%	5	9	7	9	9	8	8	9	5	8	6	9	9	9	9	9
80%	9	9	7	9	9	8	9	9	9	9	9	9	9	9	9	9
100%	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9

## 4.4 TRL AND IRL EVALUATION LINKAGE TO PERFORMANCE MEASURES

In the procurement and management of the Mission Packages (MP's) for a system, the designated program office and manager, such as the PMS420 for the Littoral Combat Ship program, requires insight into the progress of the Development Program Offices' (DPOs) constituent mission systems and where they stand in terms of providing anticipated performance, especially the Key Performance Parameters (KPPs) of the system. These insights are critical for requisite oversight and to manage development risks. However, the issue is how program managers accurately can predict the ability of the system to satisfy KPPs while development and integration are proceeding.

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Previously, DPOs were able to use Technical Performance Measures (e.g., Technology Readiness Levels [TRL]) to monitor the developmental status of specific technologies. With the development of complex multi-capability systems, such as the LCS, understanding the status of technologies are no longer sufficient for managers to gain the requisite level of knowledge on the extent to which the KPPs, as designated by the Capability Development Document, can be accomplished for the designated system. Volkert (2009) has pointed out the compounding reasons:

1. The capabilities from the individual constituent mission systems are often being modified or utilized in manners different than that specified in their original requirement set. Thus, their known/predicted performance may be different when used in a MP SoS.
2. The constituent mission systems (capabilities) being developed by the DPOs are, in some cases, still maturing. This impacts the ability to determine KPP performance in two ways;
  - a. It drives an incremental fielding of capabilities by PMS 420, meaning the solution set for accomplishing (full or partially) a KPP will vary over time.
  - b. The capability delivered by the DPO may not provide the amount of performance anticipated/predicted by PMS 420 due to developmental challenges within the DPOs program.
3. The combination of capabilities available to choose from means that the usage and contribution of an individual capability to the performance of a KPP can vary depending upon the operational employment of the system within a SoS.

Therefore, for predicting the achieved proportional capability in a complex system, Volkert proposed an approach. Here we re-write his formula with minor changes:

$$T_{C(1,2,...,n)} = \omega_n * \alpha_{C(1,2,...,n)}$$

Where  $\alpha_{C(1,2,...)}$  represents the maximum level of performance capability the combination of technology packages (1, 2, ...) is expected to meet/provide.  $\omega_n$  represents the weighting factor representing the proportional level of performance expected at the maturity stage of  $n$ .  $T_{C(1,2,...,n)}$  thus represents the achieved performance level of the capability which can contribute to the satisfaction of the KPP. The value of  $\alpha$  would be expressed in the units of performance defined by the KPP while  $\omega$  would be unit less. For  $\omega_n$ , Volkert suggested the use of SRL for the capability at that time. In order to differentiate this with the original SRL definition that is designed for assessing the development maturity of the whole system, we introduce the new notion of a Capability System Readiness Level (SRL\_C) to measure  $\omega_n$  which represents the readiness of the Capability comprised by a specific combination of technologies and the integrations among them. For simplicity, for the rest of this section, whenever SRL is mentioned, it

means the  $SRL\_C$ . Mathematically, the procedure for calculating the  $SRL\_C$  is the same as with  $SRL$  but considers the subset of  $n$  technologies from within the system which will have to be integrated to deliver a capability  $C$ .

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#### 4.4.1 COMPONENT IMPORTANCE MEASURES

A system has variants in its physical architecture that realize certain functionality and capability. A systems engineer or acquisition manager would make trade-off decisions to find a solution for a deployable system. Thus, in order to satisfy Key Performance Parameter during the development of the system, this paper proposes to perform component importance analysis by introducing three Importance Measures (IMs) with respect to SCS: TRL/IRL, cost, and labor-hours.

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#### 4.4.2 SCS WITH RESPECT TO TRL/IRL ( $I^P$ )

The IM of TRL/IRL evaluates the impact of a change in the development maturity of an element (i.e. technology or integration) on system development maturity. That is, IM measures the change of the  $SRL$  when the TRL or IRL of a specific element changes from its current value to a target value. For example, let  $SRL(TRL, IRL)$  denote the current  $SRL$  of the system, and  $SRL(TRL, IRL | TRL_i = \overline{TRL}_i)$  ( $SRL(TRL, IRL | IRL_{ij} = \overline{IRL}_{ij})$ ) denote the resultant  $SRL$  when  $TRL_i$  ( $IRL_{ij}$ ) changes to a target maturity level  $\overline{TRL}_i$  ( $\overline{IRL}_{ij}$ ) and all other  $TRLs/IRLs$  stay on current maturity values. The definition of IM with respect to TRL/IRL ( $I^P$ ) is as follows:

$$\text{For } TRL, I_i^P = \frac{SRL(TRL, IRL | TRL_i = \overline{TRL}_i)}{SRL(TRL, IRL)}$$

$$\text{For } IRL, I_{ij}^P = \frac{SRL(TRL, IRL | IRL_{ij} = \overline{IRL}_{ij})}{SRL(TRL, IRL)}$$

$I^P$  implies the effect of change in the readiness level of a given component. A component for which the variation of the readiness level results in the largest variation of the system  $SRL$  has the highest importance.

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#### 4.4.3 SCS WITH RESPECT TO COST ( $I^C$ )

Zhang et al. (2007) suggests that classical component importance analysis ignores cost, and states that it is unrealistic to evaluate the importance of components without considering the cost. Hereby, for  $SRL$  component importance analysis, we propose to consider the economic factor. This is reasonable by noting that there are always situations where system developers have to make the investment decisions based on the



comparison of the immediate return on the investment of dollars needed to mature components. Presumably, especially with a tight budget, developers allocate resources to the component that can result in the highest system maturity. Therefore, we propose  $I^{CT}$  as an IM that takes into account the cost for maturing components to facilitate such comparisons. Since the cost to mature different components varies and improvements in different components have different effects on SRL, the IM that takes into account the development cost serves as a baseline to compare the investment returns from different components. Let  $CT_i = CT_{TRL} - CT_{TRL_i}$  denote the associated development cost for maturing  $TRL_i$  from its current readiness level to a target level  $\overline{TRL}_i$ , and  $CT_{ij} = CT_{TRL} - CT_{TRL_{ij}}$  denote the associated development cost from maturing  $TRL_{ij}$  from its current readiness level to a target level  $\overline{TRL}_{ij}$ . The formula to calculate the  $I^{CT}$  is as follows:

$$\text{For } TRL, I_i^{CT} = \frac{\Delta SRL}{CT_i} = \frac{SRL(TRL, IRL | TRL_i = \overline{TRL}_i) - SRL(TRL, IRL)}{CT_{\overline{TRL}_i} - CT_{TRL_i}}$$

$$\text{For } IRL, I_{ij}^{CT} = \frac{\Delta SRL}{CT_{ij}} = \frac{SRL(TRL, IRL | IRL_{ij} = \overline{IRL}_{ij}) - SRL(TRL, IRL)}{CT_{\overline{IRL}_{ij}} - CT_{IRL_{ij}}}$$

$I^{CT}$  implies the effect of the cost to mature a given component on SRL, and the component whose readiness improvement from the investment results in the largest gain of SRL has the highest importance.

#### 4.4.4 SCS WITH RESPECT TO LABOR-HOURS ( $I^{LH}$ )

Besides the consideration of cost, there are other situations (e.g. when only certain labor-hours are available) where developers care more about the return on the effort needed to improve components. Therefore, we propose another importance measure ( $I^{LH}$ ) that takes into account the associated labor-hours to upgrade the component

readiness level in order to mature the SRL. Let  $LH_i = LH_{TRL} - LH_{TRL_i}$  denote the associated development labor-hours for developing  $TRL_i$  from its current status to a target level  $\overline{TRL}_i$ , and  $LH_{ij} = LH_{TRL} - LH_{TRL_{ij}}$  denote the associated development labor-hours for developing  $TRL_{ij}$  from its current status to a target level  $\overline{TRL}_{ij}$ , then the formula for  $I^{LH}$  is as follows:

$$\text{For } TRL, I_i^{LH} = \frac{\Delta SRL}{LH_i} = \frac{SRL(TRL, IRL | TRL_i = \overline{TRL}_i) - SRL(TRL, IRL)}{LH_{\overline{TRL}_i} - LH_{TRL_i}}$$

$$\text{For } IRL, I_{ij}^{LH} = \frac{\Delta SRL}{LH_{ij}} = \frac{SRL(TRL, IRL | IRL_{ij} = \overline{IRL}_{ij}) - SRL(TRL, IRL)}{LH_{\overline{IRL}_{ij}} - LH_{IRL_{ij}}}$$

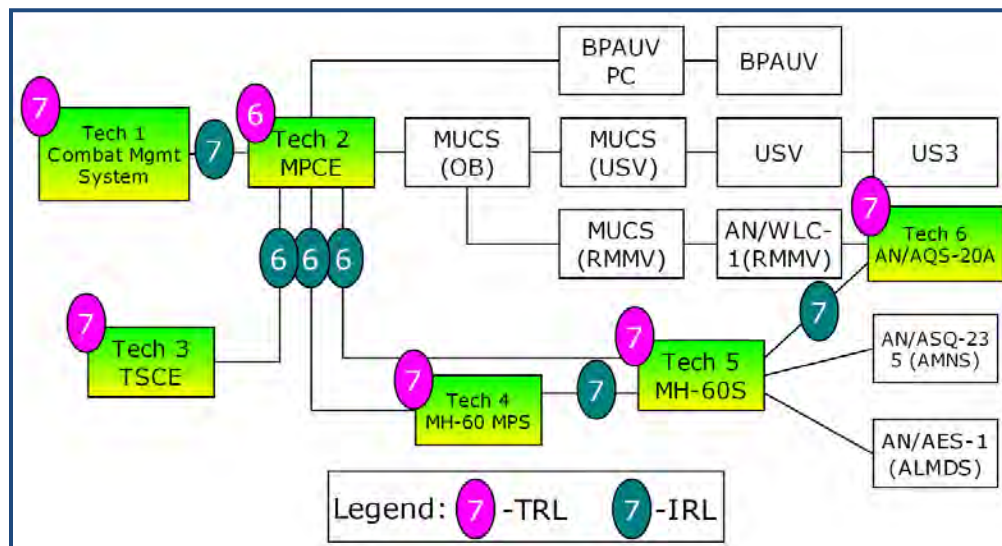


$I^{LH}$  implies the effect of the labor-hours or effort to mature a given component on SRL. The component whose readiness improvement from the investment of labor-hours results in the largest gain of SRL has the highest importance.

#### 4.4.5 EXAMPLE: RESULTS AND DISCUSSION

The following example was used in (Forbes et al., 2009) to illustrate the application of SRL. The system is designed to perform six capabilities. For the illustration of the proposed methodology in this paper, it is assumed that the *mine-detection capability* that is enabled by the combination of the shaded components is the KPP of interest. This capability has six components with six integrations among them, and the corresponding TRLs and IRLs are shown in Figure 9.

The current capability SRL for the Mine-Detection is 0.622. According to Figure 7, this value indicates that the capability is undergoing the Engineering & Manufacturing Development phase. During this phase, the major assignments are to develop system capability or (increments thereof), reduce integration and manufacturing risk, ensure operational supportability, minimize logistics footprint, implement human systems integration, design for production, ensure affordability and protection of critical program information, and demonstrate system integration, interoperability, safety and utility.



**Figure 9: Diagram of a System with Components Shaded for the KPP**

Since we are proposing to take into account the resource consumption (cost and labor-hour) in the component importance evaluation, Tables 12 and 13 show these values for maturing the components (i.e., TRL and IRL) of the capability of interest. The cost is in thousand of dollars (\$1,000), and the effort is in labor-hours. For example, it requires 599 hours of effort and \$980,000 to move Technology 1 from level 7 to level 8. It is the obligation of the program manager to obtain these estimates of resource consumption in

reality. To mature the whole capability, the estimated cost and effort equal \$17,141,000 and 10,976 of labor-hours, respectively.

**Table 12 – Resource Consumption for TRL Upgrade**

	Tech 1		Tech 2		Tech 3		Tech 4		Tech 5		Tech 6	
TRL	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time
1	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0
2	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0
3	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0
4	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0
5	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0
6	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0
7	\$0	0	\$579	453	\$0	0	\$0	0	\$0	0	\$0	0
8	\$980	599	\$157	177	\$973	541	\$459	154	\$443	551	\$410	580
9	\$820	290	\$918	267	\$404	582	\$592	341	\$490	304	\$871	358
<b>Sum</b>	<b>\$1,800</b>	<b>889</b>	<b>\$1,654</b>	<b>897</b>	<b>\$1,377</b>	<b>1123</b>	<b>\$1,051</b>	<b>495</b>	<b>\$933</b>	<b>855</b>	<b>\$1,281</b>	<b>938</b>

**Table 13 – Resource Consumption for IRL Upgrade**

	1,2		2,3		2,4		2,5		4,5		5,6	
IRL	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time
1	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0
2	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0
3	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0
4	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0
5	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0
6	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0	\$0	0
7	\$0	0	\$754	414	\$968	509	\$317	524	\$0		\$0	0
8	\$906	478	\$382	90	\$159	490	\$853	563	\$613	392	\$468	551
9	\$983	280	\$735	220	\$648	248	\$648	147	\$374	370	\$237	503
<b>Sum</b>	<b>\$1,889</b>	<b>758</b>	<b>\$1,871</b>	<b>724</b>	<b>\$1,775</b>	<b>1247</b>	<b>\$1,818</b>	<b>1234</b>	<b>\$987</b>	<b>762</b>	<b>\$705</b>	<b>1054</b>

With the proposed component Importance Measures for  $I^P$ ,  $I^{CT}$ , and  $I^{LH}$ , this paper considers two scenarios for each measure to identify the importance of components towards achieving the KPP in question. While keeping all the other components constant, the two scenarios are to advance the current maturity of a component to (1) the next level, which is  $\overline{TRL}_i = TRL_i + 1$  or  $\overline{IRL}_{ij} = IRL_{ij} + 1$ , and (2) increasing to its highest level, which is  $\overline{TRL}_i = 9$  or  $\overline{IRL}_{ij} = 9$ .

#### 4.4.6 INCREASING COMPONENT READINESS BY ONE LEVEL

By increasing the component maturity by one level, Table 14 shows the results of the calculation. For the  $I^P$  component importance, Technology 2 is the most important component whose change in maturity has the largest impact on the maturity of the capability. When Technology 2 is increased by one level, the Capability SRL is upgraded from its current value of 0.622 to 0.646, and gives an  $I^P$  of 1.039. If the objective is to have the most increase in Capability SRL if only one component can be changed by one level, then Technology 2 is the most important one. The second and third most important components identified are Technologies 5 and 6, with an  $I^P$  of 1.031 and 1.021, respectively.

**Table 14 – Component Importance for the Scenario of Increasing by One Level**

	Component	Current Readiness Level	SRL	$I^P$	$I^P$ Importance Rank	$I^{CT}$	$I^{CT}$ Importance Rank	$I^{LH}$	$I^{LH}$ Importance Rank
Technology	1	7	0.634	1.0195	5	1.2E-5	8	2.0E-5	8
	<b>2</b>	<b>6</b>	<b>0.646</b>	<b>1.0390</b>	<b>1</b>	4.2E-5	2	5.4E-5	2
	3	7	0.634	1.0189	6	1.2E-5	9	2.2E-5	6
	<b>4</b>	<b>7</b>	<b>0.634</b>	1.0197	4	2.7E-5	4	<b>7.9E-5</b>	<b>1</b>
	<b>5</b>	<b>7</b>	<b>0.641</b>	1.0307	2	<b>4.3E-5</b>	<b>1</b>	3.5E-5	3
	6	7	0.635	1.0207	3	3.1E-5	3	2.2E-5	4
Integration	1,2	7	0.631	1.0146	8	1.0E-5	11	1.9E-5	10
	2,3	6	0.631	1.0146	9	1.2E-5	10	2.2E-5	5
	2,4	6	0.629	1.0112	11	7.2E-6	12	1.4E-5	11
	2,5	6	0.628	1.0096	12	1.9E-5	6	1.1E-5	12
	4,5	7	0.631	1.0135	10	1.4E-5	7	2.1E-5	7
	5,6	7	0.633	1.0174	7	2.3E-5	5	2.0E-5	9

For the  $I^{CT}$  component importance, Technology 5 is the most importance with an  $I^{CT}$  of  $4.3 \times 10^{-5}$  indicating that the capability SRL will be increased by  $4.3 \times 10^{-5}$  for each dollar spent on maturing this technology. When considering budget allocation from a perspective of maturing the capability, Technology 5 is the most cost-effective component. The second and third most important components are Technologies 2 and 6.

Analyzing the  $I^{LH}$  component importance in the same way, we found that Technology 4, with an  $I^{LH}$  of  $7.9 \times 10^{-5}$  has the most impact on capability. The capability SRL will be upgraded by  $7.9 \times 10^{-5}$  for every labor-hour spent on maturing this technology. When considering effort allocation from a perspective of maturing the capability, Technology 4 is the most effort-effective component. The second and third most important components are Technologies 2 and 5.

Figure 10 puts together the component importance evaluation from applying the three IMs to the capability of the system. The left vertical axis is the scale for  $I^P$ , and the right for  $I^{CT}$  and  $I^{LH}$ . Black bars represent the  $I^P$  importance with respect to the importance factor of TRL/IRL for the corresponding component, white bars for the  $I^{CT}$  importance with respect to cost, and grey bar for the  $I^{LH}$  importance with respect to effort. The higher the bar, the more important is that component with respect to the importance factor represented by the corresponding color.

Therefore, for the scenario of increasing by one level, Technologies 2, 5 and 6 are relatively more important than the other components with respect to TRL/IRL; Technologies 5, 2 and 6 are relatively more important than others with respect to cost; Technologies 4, 2 and 5 are relatively more important than others with respect to effort. When all three importance factors are considered simultaneously, Technologies 2, 4 and 5 are comparably more important components for the capability development within the system. Furthermore, Figure 10 implies, in general, that technologies are more important than integrations based on the current development maturity status of the system.

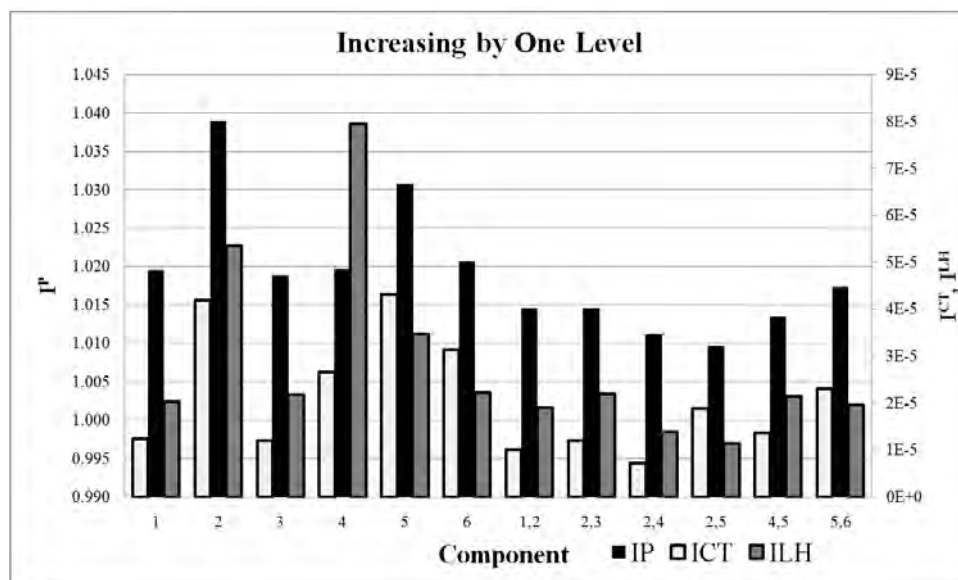


Figure 10: Component Importance Comparison for Increasing by One Level

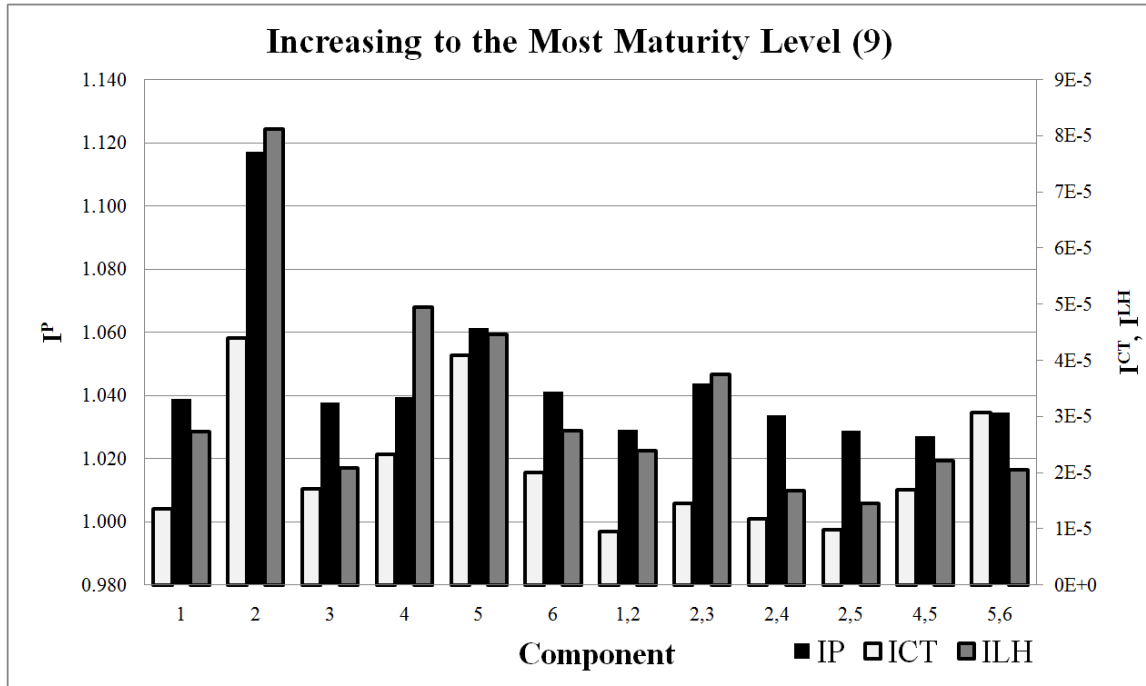
#### 4.4.7 FULLY MATURING COMPONENTS

For the scenario of increasing the component to its highest maturity level, Table 15 shows the results for considering each importance factor. Technology 2 is the most important component for all three factors, indicating the significant impact of fully maturing this technology on the maturity of the capability of the system. Therefore, resources must be prioritized towards the development of Technology 2 so as to ensure the satisfaction of the KPP of this system.

For the consideration of importance factor of TRL/IRL, Technology 5 and Integration 2, 3 are the second and third most important components. Technology 5 and Integration 5, 6 are the second and third most important with respect to developmental cost. Technologies 4 and 5 are the second and third most important with respect to developmental effort. It should be noted here that some integrations also stand as very important components for maturing the capability to satisfy the KPP of the system. Again, results of component importance calculation with respects to all three factors are plotted together in Figure 11 for comparison purpose.

**Table 15 – Component Importance for the Scenario of Increasing to the Most Mature Level**

	Component	Current Readiness Level	SRL	IP	IP Importance Rank	ICT	ICT Importance Rank	ILH	ILH Importance Rank
<b>Technology</b>	1	7	0.646	1.0390	6	1.3E-5	9	2.7E-5	6
	<b>2</b>	<b>6</b>	<b>0.695</b>	<b>1.1171</b>	<b>1</b>	<b>4.4E-5</b>	<b>1</b>	<b>8.1E-5</b>	<b>1</b>
	3	7	0.646	1.0377	7	1.7E-5	6	2.1E-5	9
	4	7	0.647	1.0394	5	2.3E-5	4	4.9E-5	2
	5	7	0.660	1.0614	2	4.1E-5	2	4.5E-5	3
	6	7	0.648	1.0413	4	2.0E-5	5	2.7E-5	5
<b>Integration</b>	1,2	7	0.640	1.0291	10	9.6E-6	12	2.4E-5	7
	2,3	6	0.649	1.0437	3	1.5E-5	8	3.8E-5	4
	2,4	6	0.643	1.0337	9	1.2E-5	10	1.7E-5	11
	2,5	6	0.640	1.0288	11	9.8E-6	11	1.5E-5	12
	4,5	7	0.639	1.0270	12	1.7E-5	7	2.2E-5	8
	5,6	7	0.644	1.0347	8	3.1E-5	3	2.0E-5	10



**Figure 11: Component Importance Comparison for Increasing to the Most Mature Level**

## 5 APPENDIX A: INTEGRATION READINESS LEVEL

Below is a series of tables that contain a list of decision criteria related to each IRL level. It should also be emphasized that the lists are not considered to be comprehensive or complete; they are merely an attempt to capture some of the more important decision criteria associated with integration maturity in order to afford practitioners the opportunity to assess the criticality of each decision criteria relative to the IRL it is listed under. Thus, to establish further verification and validation to the decision criteria, we deployed a survey that asked Subject Matter Experts (SMEs) to evaluate each decision criteria in the context of its criticality to the specified IRL. The criticality criteria for assessing the IRL decision criteria were defined as:

- Critical – IRL cannot be assessed without it
- Essential – without it, IRL can be assessed but with low to medium confidence in the results
- Enhancing – without it, IRL can be assessed with medium to high confidence in the results
- Desirable – without it, IRL can be assessed with very high confidence in the results
- N/A – the metric is not applicable to the IRL assessment

For more details on this study and its results see (Sauser et al., 2010).

**Table 16: IRL 1 Decision Criteria and Criticality Assessment**

IRL 1 Decision Criteria	Relative Frequency (RF); n = 33					Cumulative RF	
	Critical	Essential	Enhancing	Desirable	N/A	Critical Essential	Enhancing Desirable
<b>1.1 Principal integration technologies have been identified</b>	0.58	0.33	0.03	0.06	0.00	0.91	0.09
1.2 Top-level functional architecture and interface points have been defined	0.39	0.52	0.06	0.03	0.00	0.91	0.09
1.3 Availability of principal integration technologies is known and documented	0.15	0.39	0.36	0.06	0.03	0.55	0.42
1.4 Integration concept/plan has been defined/drafted	0.18	0.45	0.21	0.12	0.03	0.64	0.33
1.5 Integration test concept/plan has been defined/drafted	0.12	0.36	0.33	0.18	0.00	0.48	0.52
1.6 High-level Concept of Operations and principal use cases have been defined/drafted	0.06	0.21	0.55	0.15	0.03	0.27	0.70
1.7 Integration sequence approach/schedule has been defined/drafted	0.06	0.36	0.33	0.21	0.03	0.42	0.55
1.8 Interface control plan has been defined/drafted	0.03	0.12	0.67	0.18	0.00	0.15	0.85
1.9 Principal integration and test resource requirements (facilities, hardware, software, surrogates, etc.) have been defined/identified	0.09	0.36	0.30	0.18	0.06	0.45	0.48
1.10 Integration & Test Team roles and responsibilities have been defined	0.12	0.24	0.33	0.24	0.06	0.36	0.58



**Table 17: IRL 2 Decision Criteria and Criticality Assessment**

IRL 2 Decision Criteria	Relative Frequency (RF); n = 33					Cumulative RF	
	Critical	Essential	Enhancing	Desirable	N/A	Critical Essential	Enhancing Desirable
2.1 Principal integration technologies function as stand-alone units	0.18	0.27	0.24	0.30	0.00	0.45	0.55
<b>2.2 Inputs/outputs for principal integration technologies are known, characterized and documented</b>	0.52	0.36	0.06	0.06	0.00	0.88	0.12
2.3 Principal interface requirements for integration technologies have been defined/drafted	0.39	0.33	0.24	0.03	0.00	0.73	0.27
2.4 Principal interface requirements specifications for integration technologies have been defined/drafted	0.27	0.45	0.24	0.03	0.00	0.73	0.27
2.5 Principal interface risks for integration technologies have been defined/drafted	0.06	0.24	0.61	0.09	0.00	0.30	0.70
2.6 Integration concept/plan has been updated	0.06	0.42	0.42	0.09	0.00	0.48	0.52
2.7 Integration test concept/plan has been updated	0.09	0.27	0.52	0.12	0.00	0.36	0.64
2.8 High-level Concept of Operations and principal use cases have been updated	0.12	0.18	0.45	0.21	0.03	0.30	0.67
2.9 Integration sequence approach/schedule has been updated	0.09	0.27	0.45	0.18	0.00	0.36	0.64
2.10 Interface control plan has been updated	0.06	0.30	0.61	0.03	0.00	0.36	0.64
2.11 Integration and test resource requirements (facilities, hardware, software, surrogates, etc.) have been updated	0.15	0.39	0.27	0.15	0.03	0.55	0.42
2.12 Long lead planning/coordination of integration and test resources have been initiated	0.12	0.30	0.30	0.24	0.03	0.42	0.55
2.13 Integration & Test Team roles and responsibilities have been updated	0.03	0.15	0.58	0.21	0.03	0.18	0.79
2.14 Formal integration studies have been initiated	0.12	0.33	0.21	0.21	0.12	0.45	0.42

**Table 18: IRL 3 Decision Criteria and Criticality Assessment**

IRL 3 Decision Criteria	Relative Frequency (RF); n = 33					Cumulative RF	
	Critical	Essential	Enhancing	Desirable	N/A	Critical Essential	Enhancing Desirable
3.1 Preliminary Modeling & Simulation and/or analytical studies have been conducted to identify risks & assess compatibility of integration technologies	0.18	0.36	0.45	0.00	0.00	0.55	0.45
3.2 Compatibility risks and associated mitigation strategies for integration technologies have been defined (initial draft)	0.09	0.39	0.52	0.00	0.00	0.48	0.52
3.3 Integration test requirements have been defined (initial draft)	0.15	0.48	0.24	0.12	0.00	0.64	0.36
3.4 High-level system interface diagrams have been completed	0.48	0.27	0.24	0.00	0.00	0.76	0.24
<b>3.5 Interface requirements are defined at the concept level</b>	0.24	0.70	0.06	0.00	0.00	0.94	0.06
3.6 Inventory of external interfaces is completed	0.24	0.33	0.42	0.00	0.00	0.58	0.42
3.7 Data engineering units are identified and documented	0.06	0.45	0.24	0.21	0.03	0.52	0.45
3.8 Integration concept and other planning documents have been modified/updated based on preliminary analyses	0.18	0.27	0.42	0.09	0.03	0.45	0.52

**Table 19: IRL 4 Decision Criteria and Criticality Assessment**

IRL 4 Decision Criteria	Relative Frequency (RF); n = 33					Cumulative RF	
	Critical	Essential	Enhancing	Desirable	N/A	Critical Essential	Enhancing Desirable
4.1 Quality Assurance plan has been completed and implemented	0.18	0.27	0.36	0.15	0.03	0.45	0.52
4.2 Cross technology risks have been fully identified/characterized	0.12	0.52	0.33	0.03	0.00	0.64	0.36
4.3 Modeling & Simulation has been used to simulate some interfaces between components	0.06	0.24	0.70	0.00	0.00	0.30	0.70
4.4 Formal system architecture development is beginning to mature	0.09	0.52	0.36	0.03	0.00	0.61	0.39
<b>4.5 Overall system requirements for end users' application are known/baselined</b>	0.24	0.55	0.15	0.06	0.00	0.79	0.21
4.6 Systems Integration Laboratory/Software test-bed tests using available integration technologies have been completed with favorable outcomes	0.09	0.52	0.36	0.03	0.00	0.61	0.39
4.7 Low fidelity technology "system" integration and engineering has been completed and tested in a lab environment	0.06	0.36	0.52	0.06	0.00	0.42	0.58
4.8 Concept of Operations, use cases and Integration requirements are completely defined	0.12	0.30	0.55	0.00	0.03	0.42	0.55
4.9 Analysis of internal interface requirements is completed	0.09	0.61	0.27	0.03	0.00	0.70	0.30
4.10 Data transport method(s) and specifications have been defined	0.12	0.36	0.48	0.03	0.00	0.48	0.52
4.11 A rigorous requirements inspection process has been implemented	0.27	0.30	0.21	0.21	0.00	0.58	0.42

**Table 20: IRL 5 Decision Criteria and Criticality Assessment**

IRL 5 Decision Criteria	Relative Frequency (RF); n = 33					Cumulative RF	
	Critical	Essential	Enhancing	Desirable	N/A	Critical Essential	Enhancing Desirable
<b>5.1 An Interface Control Plan has been implemented (i.e., Interface Control Document created, Interface Control Working Group formed, etc.)</b>	0.33	0.58	0.06	0.00	0.03	0.91	0.06
5.2 Integration risk assessments are ongoing	0.06	0.48	0.45	0.00	0.00	0.55	0.45
5.3 Integration risk mitigation strategies are being implemented & risks retired	0.03	0.52	0.39	0.06	0.00	0.55	0.45
5.4 System interface requirements specification has been drafted	0.39	0.36	0.24	0.00	0.00	0.76	0.24
5.5 External interfaces are well defined (e.g., source, data formats, structure, content, method of support, etc.)	0.27	0.55	0.18	0.00	0.00	0.82	0.18
5.6 Functionality of integrated configuration items (modules/functions/assemblies) has been successfully demonstrated in a laboratory/synthetic environment	0.21	0.52	0.27	0.00	0.00	0.73	0.27
5.7 The Systems Engineering Management Plan addresses integration and the associated interfaces	0.15	0.18	0.33	0.12	0.21	0.33	0.45
5.8 Integration test metrics for end-to-end testing have been defined	0.12	0.33	0.52	0.03	0.00	0.45	0.55
5.9 Integration technology data has been successfully modeled and simulation	0.06	0.67	0.18	0.09	0.00	0.73	0.27

**Table 21: IRL 6 Decision Criteria and Criticality Assessment**

IRL 6 Decision Criteria	Relative Frequency (RF); n = 33					Cumulative RF	
	Critical	Essential	Enhancing	Desirable	N/A	Critical Essential	Enhancing Desirable
6.1 Cross technology issue measurement and performance characteristic validations completed	0.27	0.39	0.33	0.00	0.00	0.67	0.33
6.2 Software components (operating system, middleware, applications) loaded onto subassemblies	0.45	0.33	0.12	0.03	0.06	0.79	0.15
<b>6.3 Individual modules tested to verify that the module components (functions) work together</b>	0.48	0.42	0.09	0.00	0.00	0.91	0.09
6.4 Interface control process and document have stabilized	0.09	0.48	0.36	0.03	0.03	0.58	0.39
6.5 Integrated system demonstrations have been successfully completed	0.21	0.58	0.15	0.06	0.00	0.79	0.21
6.6 Logistics systems are in place to support Integration	0.12	0.42	0.27	0.18	0.00	0.55	0.45
6.7 Test environment readiness assessment completed successfully	0.06	0.52	0.33	0.06	0.03	0.58	0.39
6.8 Data transmission tests completed successfully	0.18	0.64	0.06	0.06	0.06	0.82	0.12

**Table 22: IRL 7 Decision Criteria and Criticality Assessment**

IRL 7 Decision Criteria	Relative Frequency (RF); n = 33					Cumulative RF	
	Critical	Essential	Enhancing	Desirable	N/A	Critical Essential	Enhancing Desirable
<b>7.1 End-to-end Functionality of Systems Integration has been successfully demonstrated</b>	0.61	0.18	0.21	0.00	0.00	0.79	0.21
7.2 Each system/software interface tested individually under stressed and anomalous conditions	0.33	0.55	0.12	0.00	0.00	0.88	0.12
7.3 Fully integrated prototype demonstrated in actual or simulated operational environment	0.42	0.45	0.09	0.03	0.00	0.88	0.12
7.4 Information control data content verified in system	0.24	0.55	0.18	0.00	0.03	0.79	0.18
7.5 Interface, Data, and Functional Verification	0.33	0.55	0.09	0.03	0.00	0.88	0.12
7.6 Corrective actions planned and implemented	0.15	0.48	0.27	0.09	0.00	0.64	0.36

**Table 23: IRL 8 Decision Criteria and Criticality Assessment**

IRL 8 Decision Criteria	Relative Frequency (RF); n = 33					Cumulative RF	
	Critical	Essential	Enhancing	Desirable	N/A	Critical Essential	Enhancing Desirable
<b>8.1 All integrated systems able to meet overall system requirements in an operational environment</b>	0.85	0.12	0.03	0.00	0.00	0.97	0.03
8.2 System interfaces qualified and functioning correctly in an operational environment	0.61	0.36	0.03	0.00	0.00	0.97	0.03
8.3 Integration testing closed out with test results, anomalies, deficiencies, and corrective actions documented	0.39	0.52	0.09	0.00	0.00	0.91	0.09
8.4 Components are form, fit, and function compatible with operational system	0.42	0.48	0.06	0.03	0.00	0.91	0.09
8.5 System is form, fit, and function design for intended application and operational environment	0.42	0.45	0.09	0.03	0.00	0.88	0.12
8.6 Interface control process has been completed/closed-out	0.24	0.45	0.24	0.06	0.00	0.70	0.30
8.7 Final architecture diagrams have been submitted	0.36	0.12	0.42	0.09	0.00	0.48	0.52
8.8 Effectiveness of corrective actions taken to close-out principal design requirements has been demonstrated	0.24	0.48	0.24	0.03	0.00	0.73	0.27
8.9 Data transmission errors are known, characterized and recorded	0.36	0.33	0.21	0.09	0.00	0.70	0.30
8.10 Data links are being effectively managed and process improvements have been initiated	0.18	0.52	0.27	0.03	0.00	0.70	0.30

**Table 16: IRL 9 Decision Criteria and Criticality Assessment**

IRL 9 Decision Criteria	Relative Frequency (RF); n = 33					Cumulative RF	
	Critical	Essential	Enhancing	Desirable	N/A	Critical Essential	Enhancing Desirable
<b>9.1 Fully integrated system has demonstrated operational effectiveness and suitability in its intended or a representative operational environment</b>	0.82	0.09	0.09	0.00	0.00	0.91	0.09
9.2 Interface failures/failure rates have been fully characterized and are consistent with user requirements	0.64	0.27	0.06	0.03	0.00	0.91	0.09
9.3 Lifecycle costs are consistent with user requirements and lifecycle cost improvement initiatives have been initiated	0.24	0.42	0.21	0.09	0.03	0.67	0.30

## 6 APPENDIX B: REFERENCES

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